PB84-157858

Assessment of Innovative Techniques to Detect Waste Impoundment Liner Failures

EarthTech Research Corp., Baltimore, MD

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Feb 84

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-84-041	2.	3. RECIPIENT'S ACCESSION NO. PB84 157858
4. TITLE AND SUBTITLE ASSESSMENT OF INNOVATIVE TECHNIQUES TO DETECT WASTE IMPOUNDMENT LINER FAILURES		5. REPORT DATE February 1984 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) M. J. Waller, J. L. Davis		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS EarthTech, Incorporated Baltimore, Maryland 21227		10. PROGRAM ELEMENT NO. CBRD1A 11. CONTRACT/GRANT NO. 68-03-3029
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory--Cin., OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Final 10/80 - 6/82 14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES

Project Officer: Carlton C. Wiles 513/684-7795

16. ABSTRACT

The goal of the program was to identify and evaluate nondestructive monitoring techniques for their ability to detect a leak in either existing or planned waste impoundment liners. In the case of existing sites, any technique that might improve the limitations of conventional groundwater quality monitoring practices was identified. Thus, any technique that can detect the presence of leachate moving out from a site before it acually contacts the groundwater was identified. In planned sites, the 1 ft^2 ($0.1\ m^2$) goal was identified as an ideal to work toward. Approximately 28 candidate geophysical techniques were reviewed in the literature survey. Of these, 20 were identified as having potential as leak detection techniques and were assessed during the ranking exercise. Survey results and the ranking matrix indicated that no single technique currently exists that is applicable in all situations, particularly in existing sites. Each geophysical technique has both theoretical and site-specific limitations, and should be used in a composite mode to maximize total capabilities.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 149
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

EPA-600/2-84-041
February 1984

PB84-157858

ASSESSMENT OF INNOVATIVE TECHNIQUES TO DETECT WASTE IMPOUNDMENT LINER FAILURES

by

Muriel Jennings Waller
J.L. Davis
EarthTech, Incorporated
Baltimore, Maryland 21227

Contract No. 68-03-3029

Project Officer

Carlton C. Wiles
Solid and Hazardous Waste Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

EPA Form 2250-4 (4-80)
(PREVIOUSLY 2IN; EPA FORM 287)

TYPING GUIDE SHEET

DISCLAIMER

The information in this document has been funded wholly or in part by the United States Environmental Protection Agency under Contract No. 68-03-3029 to EarthTech Research Corporation. It has been subject to the Agency's peer and administrative review, and it has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

The use of natural and manmade materials of low permeability to line waste disposal impoundments has been shown to be feasible; however, liner failures have occurred and caused contamination of ground water. Current monitoring programs are unable to detect the precise location of liner failures. This report provides an overview and assessment of nondestructive testing and monitoring techniques that have the potential to detect liner failures and pinpoint leak points.

EPA Form 2350-4 (4-80)

TYPING GUIDE SHEET

ABSTRACT

This report summarizes the state-of-the-art in leak detection technology. Techniques that have actually been used for leak detection as well as untested theories were identified and reviewed in the course of this extensive survey.

The goal of the program was to identify and evaluate nondestructive monitoring techniques for their ability to detect a leak in either existing or planned waste impoundment liners. In the case of existing sites any technique that might improve the limitations of conventional ground water quality monitoring practices was identified. Thus any technique that can detect the presence of leachate moving out from a site before it actually contacts the ground water was identified. In planned sites, the 1 ft^2 (0.1 m^2) goal was identified an ideal to work toward. Approximately 28 candidate geophysical techniques were reviewed in the literature survey. Of these, 20 were identified as having potential as leak detection techniques and were assessed during the ranking exercise. Any technique that clearly would not produce usable results was eliminated. Identified techniques were evaluated and assessed in a multiple ranking matrix exercise, which ranked each technique according to its leak detection potential and identified certain candidates as likely targets for future research and development.

Survey results and the ranking matrix indicated that no single technique currently exists that is applicable in all situations, particularly in existing sites. Each geophysical technique has both theoretical and site-specific limitations, and should be used in a composite mode to maximize total capabilities. In addition, direct sampling and ground water quality monitoring will be necessary to further confirm the results of the geophysical surveys. Several techniques were identified as applicable to planned sites and may ultimately lead to detection of the actual point source of a liner leak but at the time of the review no leak detection systems had been used in the field. Hypothetical applications were conceived for a leak detection program at both existing and planned sites. The results emphasized the need for a systematic approach in planning and conducting total site assessments which would ultimately allow for greater safety and a reduction in time and costs. Recommendations for future research efforts were made.

This report was submitted in fulfillment of Contract No. 68-03-3029 by EarthTech, Inc. under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period October 1, 1980 to June 30, 1982 and work was completed as of June 30, 1982.

CONTENTS

Disclaimer ii
Foreword iii
Abstract iv
Contents v
List of Figures vi
List of Tables vii
Acknowledgment viii

1. Introduction 1
    Research Program 1
    Scope of Work 3
2. Summary of Results and Recommendations 4
    State-of-the-Art Review 4
    Summary of Results 5
3. Problem Overview 6
    Program Objectives 6
    Ground-Water Contamination 7
    Lined Waste Impoundments 9
    Limitations of Current Ground-Water Quality Monitoring Techniques 10
    Phenomena Associated with Liner Leaks 13
    Applications and Limitations of Geophysical Techniques 15
    Data Acquisition and Interpretation Considerations 17
4. Multiple-Objective Ranking Matrix 20
    Matrix Assumptions 20
    Matrix Structure and Operation 27
    Definition of Terms Used in Matrix 29
    Weighting Factors 38
    Significance of the Values in the Matrix 40
    Matrix Results 44
5. Approaches to Leak Detection at Hypothetical, Existing and Planned Waste Impoundment Sites 46
    Site Properties 46
    Factors 46
6. Summary 60
    Summary 60
    Recommendations 61

References 102

Appendices

A. State-of-the-Art Review 63
B. Annotated Bibliography 107
C. Board of Consultants 140

EPA Form 2350-6 (4-80)
TYPING GUIDE SHEET

FIGURES

Number Page

1 Migration of leachate from a lined surface impoundment 8
2 Flow of contaminated water from a waste stockpile 8
3 A leachate collection system 12
4 Frequency ranges of geophysical techniques 14
5 Cost comparison of monitor wells versus geophysical approach 18
6 Flow chart for existing site 53-54
7 DC grid technique 56
8 Proposed waste dump site design 57
9 Flow chart for planned site. 58

A-1 Common electrode configurations - DC resistivity. 64
A-2 Results of resistivity soundings made at two locations downflow from site 66
A-3 Map of waste impoundment 67
A-4 Resistivity profile showing extent of leachate plume 68
A-5 Pole-dipole configuration 69
A-6 Equipotential lines on the surface of a landfill with current electrodes located on the landfill surface and outside the landfill 70
A-7 SP measurements at Gold Creek Reservoir. 74
A-8 SP measurements obtained at different times of the year at Gold Creek Reservoir 75
A-9 EM contour map of conductive plume at a depth of 30 meters 78
A-10 Growth of leachate plume over four-year period 80
A-11 Parallel EM profiles showing conductivity versus position. The high conductivity areas are caused by contaminated ground water in fractured limestone 81
A-12 Contoured data - EM/VLF techniques 82
A-13 Sketch of ground probing radar principles 84
A-14 Lateral continuity of soil horizon 87
A-15 Radar profile 88
A-16 Interpretation of radar profile 89
A-17 EM (conductivity) and radar profiles over Karst area with geologic cross-section shown below 90
A-18 Geotomographs showing changes in attenuation (gray levels) caused by chemical grout in a sandy soil. 91
A-19 Effect of discontinuities in parallel transmission lines. 92
A-20 Comparative TDR data 94

TYPING GUIDE SHEET

Number Page

A-21 Schematic diagram and flow and acoustic emission rate responses to seepage monitoring from within casing placed along axis of leaking earth dam 95
A-22 Acoustic emission during hydraulic fracture 96

TABLES

Number Page

1 Summary of candidate capabilities 21-26
2 Multiple objective ranking matrix with weights. 28
3 Applied methods summary of ranking matrix 41
4 R&D methods summary of ranking matrix 42
5 Summary of ranking matrix 43
6 Sensitivity of candidate methodologies to site properties 47-48

ACKNOWLEDGMENTS

This report was prepared by EarthTech, Inc., under sponsorship of the Municipal Environmental Research Laboratory, U.S. Environmental Protection Agency. The guidance and support of Mr. Carlton Wiles, and the Solid and Hazardous Waste Research Division, Municipal Environmental Research Laboratory, U.S. Environmental Protection Agency are gratefully acknowledged. The assistance of Dr. Henry Haxo, President of Matrecon, Inc., and Mr. Peter J. Huck, formerly of EarthTech in problem definition and report organization was invaluable. The contribution of Dr. William F. Kean, Assistant Professor of Geology at the University of Wisconsin, Milwaukee to the state-of-the-art review on electrical resistivity techniques was a valuable addition to the report. The diligent and patient efforts of Ms. Sumie Kinoshita, Ms. Patricia Gottal, Ms. Terry Gordon and Mr. Richard Layson of EarthTech Information Services, in technical editing, typing, word processing and drafting are also gratefully acknowledged.

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 387)
TYPING GUIDE SHEET

SECTION 1

INTRODUCTION

The historically plentiful supply of high quality ground water in this country was once regarded as impervious to harm, but over the past decade it has become increasingly threatened by waste disposal practices that result in the leaching or percolation of contaminants into water supply aquifers. The Federal Water Pollution Control Act Amendments of 1972 placed great emphasis on the restoration of the nation's surface waters. This regulatory action resulted in the decrease of large numbers of waste discharges directly into lakes and streams, but it also had the effect of making the land a major despository of solid and hazardous wastes. According to U.S. Environmental Protection Agency (EPA) estimates [1], U.S. industry produces approximately 35 million metric tons of hazardous wastes each year. Much of this waste will be disposed of to the land in impoundments lined with manmade or natural materials. These liners will act as barriers to contain the hazardous wastes, waste constituents, or leachate within the disposal site.

The use of manmade or natural materials of low permeability to line waste disposal impoundments has been shown to be a feasible method to prevent the escape of waste liquid components and leachate from disposal sites [2] and the subsequent contamination of the ground water. But, if liners are to accomplish this objective, information is needed to evaluate and monitor the performance of liners in-situ, both in existing waste impoundments and in proposed sites. Current monitoring programs rely primarily upon ground-water quality monitoring and, less often, the use of pressure suction lysimeters or leachate drainage systems. None of these techniques can pinpoint the location of liner failures and in the case of ground-water quality monitoring, contamination must have occurred over a period of years before detection is possible.

This report provides an overview and comparative assessment of potential nondestructive testing and monitoring techniques that could be used to detect liner failures. Techniques that have been applied in the field are reviewed along with untested theories. Current knowledge and technology related to these innovative techniques is examined. Further development and application of the techniques discussed here will eventually allow appropriate repair measures to be taken in time to prevent or minimize environmental damage when waste impoundment failure occurs.

RESEARCH PROGRAM

At present, despite the numerous lined impoundments and disposal sites in use throughout this country, methods to monitor the performance of liners have not been adequately developed. A monitoring system ideally should provide warning before significant environmental damage can occur, should liner failures take place at a site. Further, such a system must be capable of locating a leak position with precision, so that remedial action can concentrate on the faulty area, and must be as nondestructive in nature as possible. Treating an entire site, once the presence of a leak has been established, can be a monumental and costly undertaking; in addition, the cost for treating a complete site when only a small area may actually be affected, is a misdirection of resources. Remedial action repairs need to be concentrated on liner areas which have actually failed if resources are to be conserved. Efforts spent in determining the precise location of liner system leaks may be repaid many times by the reduced impacts of environmental damage, leading to costly litigation, and by the reduced cost of subsequent repair programs.

The overall objective of this program has been to develop recommendations for systems that will permit effective detection and location of leaks in both new and existing waste impoundments, as well as for solid wastes. Both solid and liquid impoundment sites have been considered, but emphasis has been placed on liquid waste impoundments since they have greater potential to damage the environment.

Since the problem of liner performance assessment and liner leak detection in existing sites varies in approach and complexity from the problem in sites that are planned for some future date, each situation has been considered separately. In the case of existing sites, the leak detection program faces limited options due to site considerations, areal extent, depth of impoundment, and the presence of waste already in the landfill, and thus will be almost totally site dependent. For sites still in the planning stage, it will be possible to tailor the site to a monitoring program. Thus, it may be possible to emplace a leak detection system directly underlying a planned site prior to construction, or even to select a configuration for site layout that will readily lend itself to a routine monitoring program.

At the outset of this program the primary objective for each candidate detection technique was the ability to pinpoint a waste impoundment liner failure within a maximum area of 1 ft^2 (0.1 m^2). However, due to restrictions placed on detection systems at existing sites, which in most cases will limit them to surface use, it was decided to broaden this goal to encompass any system that could feasibly improve upon current conventional monitoring techniques. Therefore, any system that has the potential to detect a leachate plume prior to contact with the ground water, has been reviewed and evaluated. Generally, the techniques surveyed do not appear to be capable of meeting the initial program objective of 1 ft^2 (0.1 m^2) for existing sites. A potential exception is an electrical resistivity technique under testing by Southwest Research Institute. This technique is discussed later in Appendix A. In the case of detection techniques applied to planned disposal sites, the 1 ft^2 (0.1 m^2) goal will still pertain. Thus a distinction is made between plume detection at existing sites, and actual leak detection at planned sites.

SCOPE OF WORK

Program objectives have been met with a three-part approach beginning with a review of the literature to establish the state-of-the-art in the leak detection field and then to identify a list of possible candidate methodologies. A multiple objective ranking matrix was then designed and executed. This tool was used to rank each candidate technique against all others in the survey, according to a pre-defined set of parameters covering pertinent technical, economic, and operational objectives. Finally, each candidate was summarized, and a set of guidelines for field application of each technique, at hypothetical existing and planned sites, was prepared. The final result of this program will be the necessary information by which to rank research and development goals and allocate resources for future development of techniques that show promise as leak detection systems.

SECTION 2

SUMMARY OF RESULTS AND RECOMMENDATIONS

A literature search was conducted in order to obtain relevant information and identify possible candidate methodologies undergoing laboratory research or being applied in the field as leak detection systems in existing or planned lined waste impoundments. A comprehensive manual investigation and a computerized search of several pertinent data bases were performed. Experts in the field were also contacted. The topics covered include pertinent mechanical and soils properties, relevant geophysical techniques, ground-water hydrology, and lined waste impoundments. Methodologies that had seen actual application or appeared to be conceptually applicable to the leak detection problem were then included for assessment in the Multiple Objective Ranking Matrix (see Section 4). Each methodology identified for assessment is discussed, and candidates that initially appeared to have application to the problem but were rejected for further consideration at the conclusion of the literature review are identified and briefly reviewed.

STATE-OF-THE-ART REVIEW

Results of the literature review provided little information on actual leak detection techniques, either in existing or planned lined waste impoundments. Considerably more information was available regarding the problem of leachate plume detection at existing sites. However, in no case was successful leachate leak detection reported prior to its detection by ground water quality monitoring, which assumes fairly widespread contamination. Although the importance of leachate plume detection in the unsaturated zone or vadose prior to actual contamination of ground water was noted by many authors, no case was found in the literature. In addition, experts in the field who were contacted on this subject could report no such case (personal communication). This is not so much a reflection of the limitation of current geophysical leak detection techniques as it is an indication of the state-of-the-practice in ground-water quality monitoring. Attempts at leak detection in existing sites tend not to be made on a routine basis until contamination is indicated by water quality analysis. No cases of techniques being applied in the field to actually evaluated liner integrity came to light during the review.

Among those techniques identified as having seen application in the field to detect a leachate plume were:

- High-Frequency Pulse
- Electromagnetics

- Resistivity
- Seismic

Resistivity techniques appear to have had the greatest field application, and thus have been discussed to a degree beyond any of the other identified techniques; these are followed by electromagnetic techniques, which are beginning to be widely applied, both for leachate plume identification as well as areal site surveys. A number of other techniques, which are either conceptually applicable or have seen field use in other applications, such as petroleum exploration, or in extensive site evaluations, were also identified.

Techniques identified for use in planned sites included:

- Time-domain reflectometry grid,
- Acoustic-emission monitoring techniques,
- D C resistivity grid,
- Pole-dipole resistivity techniques.

SUMMARY OF RESULTS

Results of the ranking matrix exercise make it clear that a composite of techniques must be used to solve the leak detection problem at existing sites. Techniques evaluated for use in such sites achieved overall lower scores due to the complexity of locating a leak from the periphery of a site. In addition, certain of the techniques that were evaluated are sensitive to the electrical properties of a leachate in the host medium while others are sensitive to elastic properties and density changes in the soil caused by the leak. Still others are sensitive to the actual fluid flow from a leak. Composite geophysical surveys can be used to monitor a variety of material properties, thus enhancing confidence in the result of a survey.

In the case of planned sites, it will be easier to design for liner performance monitoring programs at the conception of a waste impoundment program. The ability to emplace systems beneath a new site will make the goal of leak detection within 1 ft^2 (0.1 m^2) a greater probability, and will avoid major problems with cultural noise, which plague leak detection efforts at the periphery of existing sites. This technique, identified and evaluated for use in planned sites, received overall higher scores on the matrix.

Despite the problems associated with the techniques identified in the course of this program, they still hold out greater promise of success under optimum site conditions than do conventional monitoring methods.

SECTION 3

PROBLEM OVERVIEW

Recent discoveries of environmental problems at existing waste disposal sites have made clear the need for methods by which sources of leachate leakage can be identified. New liner systems and materials are being put into operation at newly constructed sites. These materials must be placed in service without extended life tests, and the possibility that unexpected faults may occur in the future cannot be discounted. In addition existing lined sites, put into service without consideration to detection of potential liner failure beyond conventional ground-water quality monitoring techniques, exist in great numbers and are a potential source of ground-water contamination. Thus the present and future need for leak detection systems is clear.

PROGRAM OBJECTIVES

The overall objective of this research program was to develop recommendations for systems that will permit effective in-situ detection of leaks in new and existing waste impoundment liner systems. The detailed objectives of the program were:

- Survey and evaluation of available information relating to nondestructive testing and monitoring techniques for locating and detecting seepage or liner failure points in existing or planned waste impoundments.
- Development of criteria to rate candidate detection techniques in terms of technical and economic feasibility.
- Evaluation and ranking of candidates to assess the feasibility of pinpointing the liner leak within a maximum area of 1 ft^2 (0.1 m^2).
- Recommendations for field application of techniques, and for allocation of future funds for research programs.

In order to meet these broad program goals, it was first necessary to develop an understanding of the ground-water contamination process, the limitations of current ground-water quality monitoring techniques, and the design and configuration of lined waste impoundments. This information dictates the operational parameters of any leak detection technique.

GROUND-WATER CONTAMINATION

The contamination process begins with sources of contaminants. The type of contaminant depends on the source and can range from hazardous organic chemicals in impounded leachates to high concentrations of salts. The contamination can occur either deliberately as in septic tanks or accidentally as from industrial wastewater impoundments. The major sources of these wastes include [3]:

1. Industrial wastewater contained in surface impoundments.
2. Municipal and industrial solid refuse and sludge disposed of on land.
3. Sewage wastes from homes and industries.
4. Municipal sewage and storm-water run-off collected, treated, and discharged to the land.
5. Municipal and industrial sludge that is land spread.
6. Brine from petroleum exploration injected into the ground or stored in evaporation pits.
7. Solid and liquid wastes from mining operations stored or disposed of in tailing piles or lagoons, or discharged.
8. Domestic, industrial, agricultural, and municipal wastewater disposed of in wells.
9. Animal feedlot waste disposed of on land and in lagoons.

It is important to note that the configuration of contamination and leachate migration from an impoundment site through the unsaturated zone to the ground water is highly site specific, depending upon local hydrogeology. Nevertheless it is possible to describe typical flow patterns of leachate for several common situations. Figure 1 illustrates the migration of leachate from a lined surface impoundment. Note that the contaminated water typically flows downward to form a recharge mound at the water table and then flows laterally outward below the water table. Figure 2 depicts the flow of contaminated water leached from a waste stockpile moving downward to the water table and, thereafter, laterally and vertically to a nearby pumping well.

Unlike surface waters, ground waters do not have a natural cleansing mechanism. Residence time of ground water in an aquifer can be as long as 200 years. As contaminants travel through the soil and into the ground water, they can be modified somewhat by various attenuation processes which are typically quite slow. Predicting the degree to which contaminants are attenuated is one of the most difficult problems facing the community today. Since the movement of ground water is typically less than 60.96mm/day, contaminants within the ground water system fail to mix with the native water. Thus they tend to travel as slugs, local plumes, or masses of degraded water. Despite this slow movement, the motion is constant, and the water is eventually

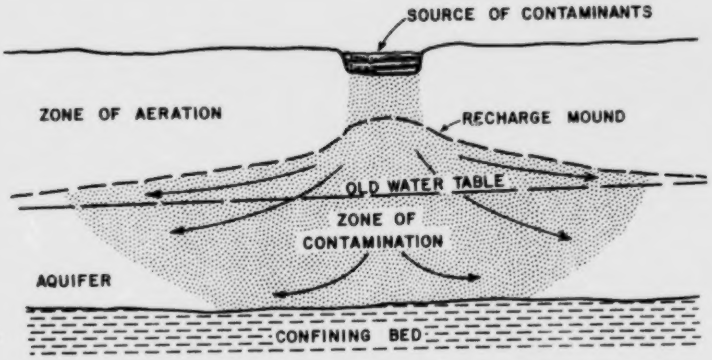

SOURCE OF CONTAMINANTS
ZONE OF AERATION
RECHARGE MOUND
OLD WATER TABLE
ZONE OF CONTAMINATION
AQUIFER
CONFINING BED

Figure 1. Migration of leachate from a lined surface impoundment.
(U.S. Environmental Protection Agency, 1977)

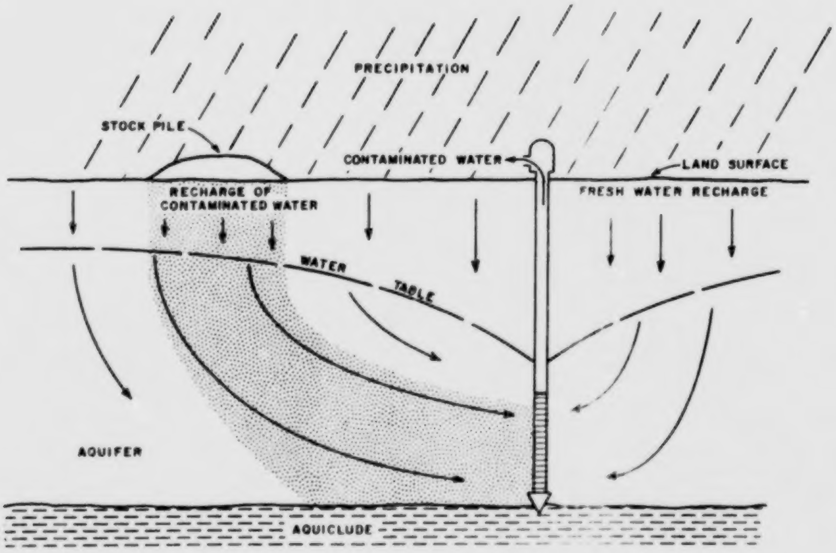

PRECIPITATION
STOCK PILE
CONTAMINATED WATER
LAND SURFACE
RECHARGE OF CONTAMINATED WATER
FRESH WATER RECHARGE
WATER TABLE
AQUIFER
AQUICLUDE

Figure 2. Flow of contaminated water from a waste stockpile.
(U. S. Environmental Protection Agency, 1977)

EPA Form 2350-4 (4-80)
(PREVIOUSLY EPA FORM 261)
TYPING GUIDE SHEET

discharged to the surface. Points of discharge include surface water bodies such as rivers and lakes and wells and springs that are used for water supplies.

Toxic chemicals such as arsenic, barium and radionuclides often occur naturally in soils, whereas contamination by synthetic organic chemicals is generally associated with byproducts of industrial processes. Chemicals such as trichloroethane, trichloroethylene, freon, acetone, xylene, dimethyl sulfoxide, trimethyl silanol, chromium, arsenic, lead, zinc, chloroform, ethylene chloride, benzene, toluene, ethyl benzene, fuel oil, vinyl chloride, and many other compounds have been found in various combinations in wells.

According to the EPA report on Proposed Ground Water Protection Strategy, Appendices, 1980, 44 communities in Massachusetts had a public water supply severely contaminated with one or more synthetic organic compounds; 16 incidents have occurred in Connecticut, 25 in Pennsylvania, 12 in New York, and one or more in each of 20 other states. EPA is currently compiling a national inventory of damage incidents that have been caused by improper disposal of municipal and industrial wastes. Ground-water contamination has been by far the most common type of damage reported, followed by surface water incidents. It is important to note that almost every known instance of ground-water contamination has been discovered only after a drinking water source has been contaminated.

LINED WASTE IMPOUNDMENTS

In the application of any leak detection system to a waste impoundment site, it is important to obtain as much knowledge as possible about liner materials, methods of installation, materials in the site itself, and the depth, size and shape of the particular impoundment site. Site characteristics, including local geography, hydrogeology, and climatic conditions, also have a role in selection of liner leak detection systems.

Materials presently used for liners include soils, asphalts, concrete, admixes, and polymeric membranes, including rubber and plastic sheetings made of polymers such as polyethylene and polyvinyl chloride. Soil liners absorb and retain contaminants from the waste fluid as it passes through. This process is referred to as attenuation. Other liner materials significantly reduce the flow of contaminants away from the impoundment site. The type of liner system employed must be compatible with the waste material because some waste materials degrade the liner material.

Typical impoundment geometries are quite variable depending upon specific site conditions, the type of waste (i.e., liquid or solid) and the type of liner system. Configurations may range from the use of an available arroyo or gully, an excavation partially below grade to an excavation completely below grade. It is important to note that impoundment sites vary in size from tens to hundreds of acres, and in depth from 10 to 30 meters. Size considerations have particular impact on the efficacy of various potential leak detection sytems.

All types of liner systems are subject to defects and failures. Membrane materials that offer the greatest degree of impermeability are also subject to a greater risk of failure. On the other hand, clay liners, which may be compacted to depths of a few meters, are unlikely to suffer sudden mechanical failures, but are subject to degradation over time due to the effects of leachate contents upon the integrity of the clay.

Liner fabrics are typically shipped from a factory in long sheets and seamed in the field. Therefore, proper seaming is essential to liner performance. Certain other characteristics of lined sites also contribute to the possibility of liner system failure, and may additionally yield information that can be used to advantage with certain leak detection methods. For example, reinforced liners are less flexible than unreinforced liners of the same material. In the presence of ground deformations, the reinforced material will transmit greater stress to the seam, and is more likely to fail at the seam than its reinforced counterpart. Such mechanical failures may be detectable by certain geophysical techniques. Additionally, the reinforcing fibers will be exposed to leachate attack at the overlap unless the edges of the fabric have been capped. If leachate is absorbed into the reinforcing fibers from the exposed ends, delamination is possible. With the exception of seam failures, which tend to open rapidly along the total length of a seam once an opening occurs, most leaks in lined sites will be point-source leaks.

Leaks in unreinforced materials can either be discrete point source leaks caused by settlements, larger leaks caused by leachate attack on the liner material or from settlement. Techniques capable of detecting point source leaks should also be applicable to larger leaks. General site and liner details may help point to the most likely mode of failure and identify areas in which detection efforts should be concentrated.

LIMITATIONS OF CURRENT GROUND-WATER QUALITY MONITORING TECHNIQUES

The limitations of current techniques routinely applied at hazardous waste impoundments to detect ground-water contamination provide the point of departure for the innovative leak detection techniques under review in this study. The three most commonly applied monitoring and detection techniques include (1) monitoring wells, (2) lysimeters, and (3) leachate underdrains.

Monitoring Wells

Monitoring wells are by far the most common means of monitoring ground water contamination at waste disposal sites. Under Section 265.91 of the Resource Conservation and Recovery Act, the four high-quality monitoring wells, one up gradient and three down gradient, are required for a surface impoundment or landfill. Unfortunately, this technique can only sample a small volume of subsurface space. An accurate analysis of site conditions would require that the number of sample stations be substantially increased. In addition, the extremely slow rate of subsurface liquid movement often results in a time lag of several years from the intitial time of leakage for a leachate plume to intersect a monitoring well. This time lag means that not only a significant volume of an aquifer has undergone contamination, but that a significant area of soil in the unsaturated zone underlying the source of the leak has undergone contamination as well. Once ground-water contamination has been detected at a site, it often becomes necessary to perform a thorough site investigation to attempt to define the extent of the leachate plume and to locate the point source of the leak. In such cases the risk of drilling can be significant. Breaching the clay seal of a trench, puncturing a drum or releasing fumes and gases, as well as possible fire or explosion, are all potential risks when drilling at hazardous material sites. Even so, extrapolation beyond and interpolation between data points are necessary when using this approach. Benson, Glaccum and Beam [4] site several cases where monitoring wells, placed at existing waste disposal sites using the "best guess" method for locating the wells, failed to detect the presence of a dump site or the occurrence of a spreading leachate plume. However, geophysical surveys from the surface were able to identify the location of the buried waste and the presence of a contaminant plume in a period of several days.

Controversy surrounds the problem of sampling and analysis of ground water and its potentially hazardous contaminants. Ground water and soil pore water by its nature are difficult to sample. On occasions, one reference cannot be totally certain if the well is being installed so that sampling will occur in the desired stratum. In addition, it is not known if the methods currently used to sample ground water are equally effective in the saturated zone as well as the unsaturated zone. Once samples are brought to the surface, additional problems are noted that involve chemical, biological and physical characterization of the ground water and its contaminants. For example, there are numerous gaps regarding methods to preserve samples and protocols to determine acute toxicity of contained wastes, and better methods are needed to relate laboratory data to those obtained in the field. [5]

In addition, both the high capital cost of installing and monitoring the wells and the cost of analytical testing make this technique an expensive ground-water protection system, considering that a degree of damage to the environment must have occurred prior to detection and that the systems cannot be used to indicate the specific location of a leak.

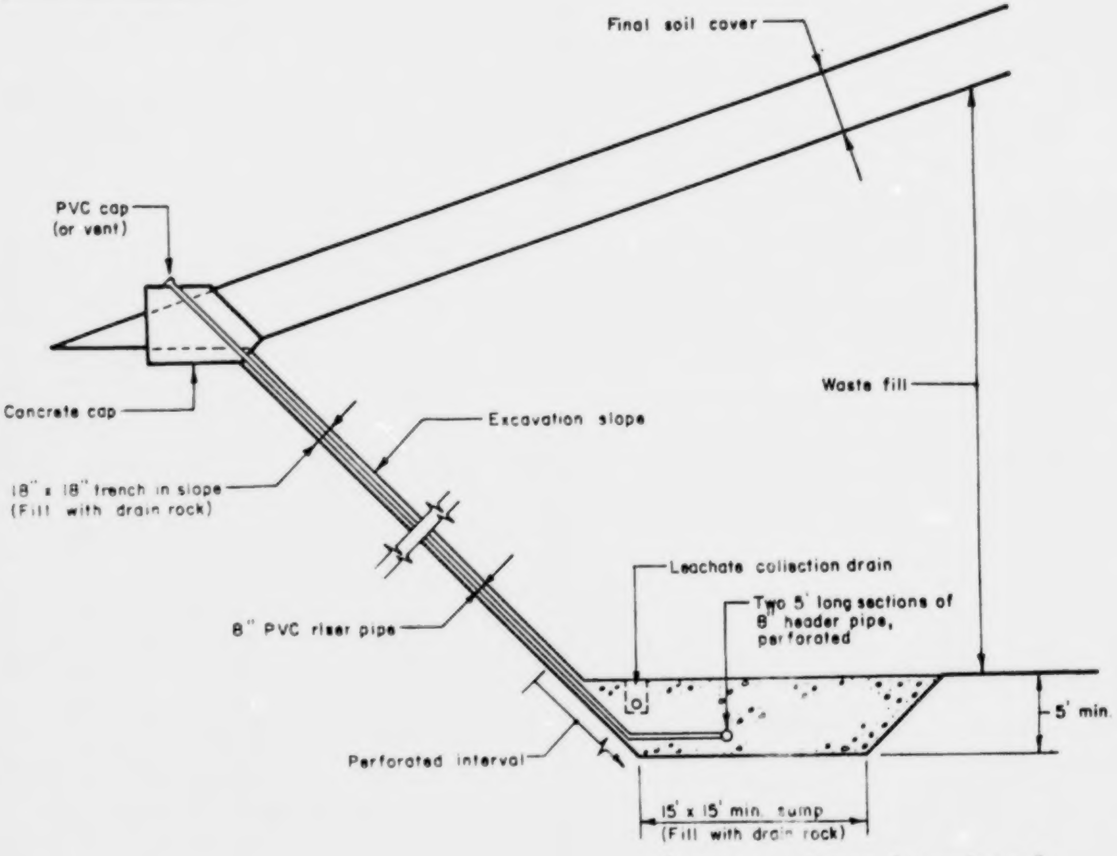
Lysimeters

Lysimeters typically are used for detecting liquids in the unsaturated or partially saturated zones of soil. Monitoring of contamination in the unsaturated zone is highly desirable because it allows detection of contaminants prior to the point at which damage to the ground water has been incurred, and can lead to faster detection of the existence of a leak, and may make it possible to come within range of the leak itself. This can also minimize the amount of soil that is contaminated.

A lysimeter is a porous ceramic cup to which liquid is taken in from the surrounding soil when a vacuum is placed on the cup. The lysimeter is subsequently pressurized and the liquid is forced to the surface for collection and analysis. Unfortunately, although this technique has certain advantages over conventional ground-water quality monitoring techniques, it once again cannot locate or pinpoint the source of the leak, which is essential in order to facilitate repair of the breached liner system, and like ground-water monitoring, must wait for the contaminant to intersect the lysimeter. In addition, lysimeters have historically experienced problems in the following areas: become clogged after a time; allow only relatively small samples to be obtained; and elements in the ceramic cup tend to degrade into the sample, causing incorrect sample analysis.

Leachate Collection Systems

Leachate collection systems are sometimes used, particularly where there is a high ground-water table or source of water infiltration, or where the degree or risk imposed by an impounded hazardous waste warrants such an undertaking. Such an underdrain system may serve to transmit fluids beneath and through an impoundment site without interacting with any contaminants from the waste impoundment (see Figure 3). According to Kays [6] an underdrain system consists of an interceptor, collector, filter, conveyor, and disposal mechanism.


Final soil cover
PVC cap
(or vent)
Concrete cap
Excavation slope
Waste fill
18" x 18" trench in slope
(Fill with drain rock)
Leachate collection drain
Two 5' long sections of
8" header pipe,
perforated
8" PVC riser pipe
5' min.
Perforated interval
15' x 15' min. sump
(Fill with drain rock)

(Source: Emcon Associates)

Figure 3. A leachate collection system.
(Matrecon, 1980)

TYPING GUIDE SHEET

The interceptor conveys seeping fluids to the collectors, which are generally located in blankets or trenches at the bottom of the impoundment facility. Filters are then required when there is a danger of the liner (clay lining) degrading into the interceptor material. The underdrain monitoring system feeds into a closed pipe conveyance. Some facilities have pumping arrangements that allow leakage and underflow to be pumped and returned to the impoundment.

Leachate collection systems help reduce the risk of a leak starting because of the negative pressure head produced. Although this system should allow any leakage from an impoundment to be detected and managed, it too has problems and drawbacks. It cannot be employed in an existing site. Any back-up in the conveyance system can result in instability to the embankment. They tend to plug with time, and they are expensive to install and require daily inspection (RCRA part 264,226). Finally, they are unable to identify the location of a leak or to facilitate repair and there is no guarantee that leachate or other contaminants are not leaking offsite.

Each of the three conventional monitoring and detection techniques reviewed above have important application in a comprehensive ground-water protection system. Each also has serious limitations. The limitations of these systems define the operational parameters and technical capabilities of the innovative techniques to be considered here.

PHENOMENA ASSOCIATED WITH LINER LEAKS

To assist in defining potential leak detection systems, certain expected phenomena associated with liner leaks were identified. Then various leak detection techniques having the ability to locate or identify these phenomena were selected. In addition, techniques that had seen field application in various environments and for a variety of purposes, as well as those which seemed to have conceptual application to the leak detection problem, were reviewed. Phenomena that might yield to leak detection techniques are identified below.

Leachate Conductivity

Leachate is typically high in ionic content and thus a relatively good electrical conductor. Assuming that intact portions of the liner are very poor conductors, it may be possible to use specialized electrical resistivity probe configurations to map the point at which the leachate penetrates the liner. Such attempts must take into account the fact that the site itself contains leachate and, possibly, a variety of conductive objects like metals.

Subgrade and Waste Impoundment Materials

Liners are typically bedded on a fine-grained, cohesive soil, and carry a cushion of soil on top. These are placed during construction, and should have electrical and mechanical properties different from the material within the cells of the impoundment. Thus, contrast may be provided that will make it possible to map the liner/subgrade interface by seismic or electromagnetic means. Areas of settlement so identified would be potential leak generating candidates, and selected for intensive inspection.

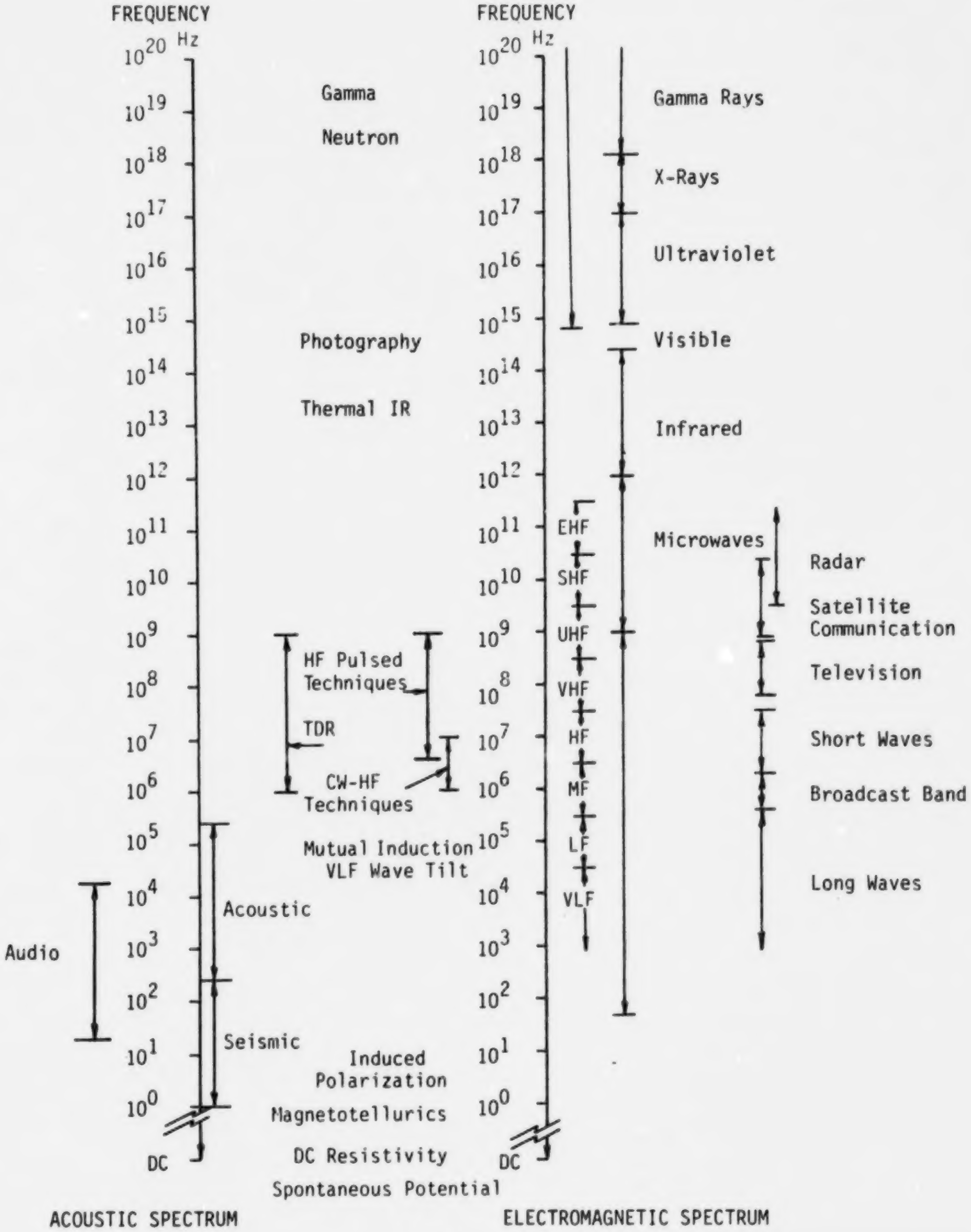


Figure 4. Frequency ranges of geophysical techniques.

EPA Form 2350-4 (4-80)
TYPING GUIDE SHEET

Ground-Water Flow Fields

Leachate point sources will be associated with relatively high hydraulic gradients, perhaps even soil piping. In the case of a well-established leachate leak, the ground-water flow field will result in a leachate plume that may be detectable outside the site by trace element analysis. Tracking the leachate plume back under the site to the leak would require meticulous, detailed hydrology, and could locate the leak only approximately at best. Further, a leachate plume in the ground water represents environmental damage that has already occurred. For those cases where this has happened, the leachate plume can be used to point toward the leak so that the more precise detection methods can be concentrated in critical areas.

Liner and Soil Distress

The liner and/or the soil may be in a state of high stress if the leak is the result of tension in the material. If this is the case at a particular site, either ground deformation monitoring or acoustic emission might be used to locate the leak area. The state of stress may have been relieved by the liner failure, or a liner failure not associated with mechanical distress may have caused a leak. If indications of distress are detected, however, a potential leak may be expected. The phenomena discussed above relate to the observation of leaks and leachate migration in both existing and planned sites. Various geophysical techniques might be applied to the detection of these phenomena under favorable site conditions. The techniques were selected for their potential capability to see out beyond their point of application, and therefore improve upon the performance of conventional monitoring techniques. In addition, they met two broad program goals:

- They can be applied to leak detection problems in-situ.
- They are nondestructive.

APPLICATIONS AND LIMITATIONS OF GEOPHYSICAL TECHNIQUES

Geophysics is defined as the application of the principles of physics to the study of the Earth [7]. The purpose of applied geophysics is to investigate and evaluate specific and relatively small scale, shallow features which exist within the Earth. Figure 4 presents a summary of frequency ranges at which the different geophysical techniques operate. According to Parasnis [8] field applications of geophysics fall into four broad classes:

- Static methods - in which the distortions of a static physical field are detected and measured in order to delineate the features producing them.
- Dynamic methods - in which signals were sent into the ground, the returning signals are detected, and their strengths and times of arrival are measured at various points.
- Relaxation methods - which measure the dimension of time needed for a disturbed medium to return to its normal state.

- Integrated effect methods - in which the detected signals are statistical averages over a given area or within a given volume.

In addition, geophysical measurement techniques may be deployed from the surface, a borehole, or even from the air. These classifications refer only to mode of operation and have no physical significance. However, under certain conditions one technique may prove superior to some other application, in terms of proximity to the phenomena being measured or the configuration of a site. Finally, geophysical techniques are generally considered to be indirect and, therefore, nondestructive (NDT), in contrast to a technique like coring, which provides direct evaluation of subsurface strata. It must be kept in mind that a core only evaluates what is in the borehole. In a nonhomogeneous medium the core data may not give a significant representation of conditions away from the borehole.

Certain geophysical techniques have application to both existing and planned sites, where as others may be employed in either one or the other. Each technique is evaluated in detail in Appendix A.

Existing Sites

The performance of a leak detection system depends upon the site environment and the impoundment contents. Any particular site may be subject to natural or cultural interferences, whether due to soil composition or the presence of stray ground currents that will degrade performance of the monitoring system.

Particular limitations inherent in geophysical sensing techniques affect their application to leak detection at existing waste disposal sites. The major drawback in field application of geophysical remote sensing techniques is the problem of receiving a signal through a conductive body (a leak) in a resistive medium (soil or liner material) underlying a conductive overburden (waste site). Thus, many of the geophysical methods are limited in the capabilities to detect leaks by the waste material itself, rendering surface measurements far from ideal; in many cases they may not be useful for detecting leaks under a site at all, and will have to rely upon their ability to detect changed conditions, over time, in the unsaturated zone, prior to the point at which a contaminant reaches the ground water. Borehole methods improve the probability of detecting leaks because potentially they can see under the site and do not have to look through it. Borehole geophysical techniques are most useful when the distance between boreholes is not greater than about 30 meters, although this distance will vary depending on the soil type and conductivity of the host material. Pole-dipole techniques undergoing investigation at Southwest Research Institute (SWRI) offer the potential of high resolution leak detection without the cultural noise problems that affect other geophysical techniques. Most techniques fail to penetrate laterally and/or vertically to greater distances. Generally, geophysical techniques are only able to resolve variations equal to or larger than 10 percent of their range. Thus a compromise must be made between the minimum spacing between measurement points and the size of leak likely to be detected. In addition, the limitation imposed upon these techniques by the dangers in placing boreholes through an existing waste dump site render their application and effectiveness questionable under many existing situations. It is hoped that the pole-dipole technique under investigation at SWRI will allow comprehensive investigation at existing sites without the need to use destructive testing methods.

Nevertheless, the use of geophysical techniques in composite surveys can increase confidence levels as to the accuracy and completeness of results. If for example, two different techniques yield similar results, it is possible to have a high level of confidence without drilling. In more ideal situations, geophysical methods can provide detailed subsurface information that would otherwise require substantial drilling to achieve spatial coverage, using conventional direct sampling techniques. The application of geophysical techniques in conjunction with conventional techniques can also realize substantial cost savings. These techniques can also realize substantial cost savings by eliminating guess work in siting monitoring wells. Figure 5 illustrates a rough cost comparison of monitoring wells alone versus geophysical approaches to site survey problems [9]. It should be noted that the figures in this graph do not relate to any specific geophysical technique, rather they represent an average cost comparison of numerous jobs conducted over time.

Planned Sites

The problem of leak detection in new, as yet unconstructed, sites while not trivial, is much less complex than for existing sites. There are a variety of sensing systems that might be placed near the liner that would be capable of detecting the presence of leachate or its effects, or of evaluating the mechanical integrity of the liner itself. Ultimately, it may be advantageous to design a system utilizing several different geophysical techniques in combination that might monitor several changes in materials properties, such as the presence of leachate and the occurrence of mechanical failures. Such a system could also be designed to detect changes in wave forms emitted from within or adjacent to the impoundment site. Several possible configurations are described and evaluated in Section 4.

In the case of planned sites, the program goal of detecting leaks within a 1 ft^2 (0.1 m^2) range becomes a very real possibility. It may eventually be possible to design an inbuilt system to meet the needs of any particular site, in terms of cost and technical precision. Thus, a small site or a municipal landfill, where less hazardous materials are impounded could use a relatively inexpensive system, monitored on a quarterly to twice yearly basis. In the case of vast impoundments for hazardous liquid wastes, where the cost of liner failures would be great, it will eventually be possible to build-in a continuous monitoring system with equipment and procedures designed for cell-by-cell monitoring and daily retrieval, processing, interpreting, analyzing, recording, and storing of liner performance data. Problems yet to be resolved in the development of such systems will be treated in Section 6.

DATA ACQUISITION AND INTERPRETATION CONSIDERATIONS

The problem of data acquisition and interpretation is of major significance to the useful application of geophysical techniques and therefore to the solution of the leak detection problem itself. It should be noted that usually better

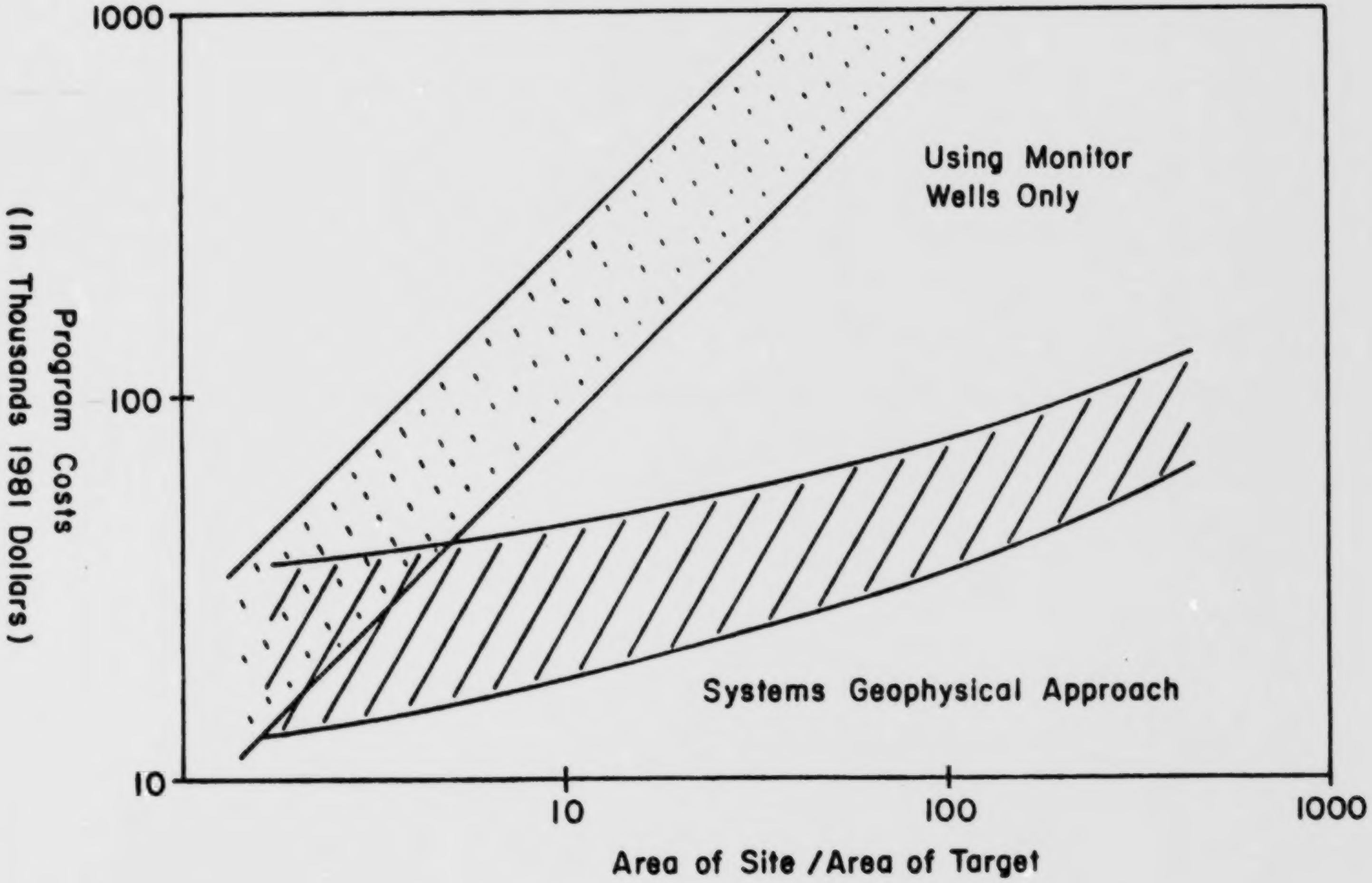


Figure 5. Cost comparison of monitor wells versus geophysical approach. (Benson, Glaccum and Beam, 1981)

quality and greater quantity of input or field data permits significantly better quality processed data; this in turn permits the data to be interpreted with a greater degree of confidence.

Often "easy to use" equipment will produce, at best, extremely limited information. Thus, inadvertently, a trade-off is often made between ease of data acquisition in the field and difficulty of data reduction and interpretation later on; time is often spent attempting to interpret results when the information being sought is not to be found in the raw data. Since the highest priority needs to be placed on solving the problem under investigation, equipment size and tediousness of actual data collection should receive extremely low priority. Although data acquisition and interpretation are too technically complex to address in depth here, several factors that will have impact upon the application of geophysical leak detection systems deserve comment.

Existing Sites

Situations can occur where any amount of data collected in the field will be useless if the instrument sensitivity (assuming the use of a specified instrument) and signal-to-noise capabilities are inadequate. Signal-to-noise is the ratio of the data being sought relative to stray signals being produced by the medium itself or by other factors present at the site. Often the waste material itself will shield the weak signals emitted by the leak. Therefore, as much care as possible is needed to obtain useful data at existing sites.

Planned Sites

Signal-to-noise problems, while not trivial at planned sites, should constitute a lesser problem than at existing sites, since they can be considered in the total leak detection system plan. However, in considering monitoring systems to provide total coverage of large lined impoundments, and to meet the broad program objective set by EPA, of 1 ft^2 (0.1 m^2) resolution, the magnitude of the data interpretation problem must be considered. A one-acre site could thus entail at least 44,000 data points to achieve the highest possible resolution. Data processing and interpretation on this scale would require substantial computer power and display capabilities, a major factor in systems economics. Obviously, the magnitude of the problem increases in proportion to the areal extent of the impoundment site.

SECTION 4

MULTIPLE-OBJECTIVE RANKING MATRIX

A multiple objective ranking matrix is a technique for comparing the effectiveness of several candidate methodologies in meeting a defined set of assessment criteria. The selection of appropriate leak detection techniques for further development will be aided in part by the results of the matrix operation. The selection of techniques for inclusion in the matrix was made on the basis of the state-of-the-art review. The techniques selected for review are summarized in Table 1. Detailed information is located in Appendix A - State-of-the-Art Review.

It is important to note that the matrix, however carefully designed and executed, is not capable of providing a fully accurate quantitative rating for each parameter and each detection method being assessed, based as it is on the results of a literature survey instead of full-scale laboratory confirmative testing. Therefore the matrix should be regarded as one tool in the problem-solving arsenal and not as an endpoint in itself.

MATRIX ASSUMPTIONS

In order to evaluate the results of the matrix exercise, an understanding of the assumptions made as a basis for matrix operations is necessary. Criteria for inclusion in the matrix included the following:

- The ability to detect leaks in-situ
- Methods must be nondestructive
- The ability to "see out" beyond the borehole, or monitoring point to a depth greater than 30 cm depth
- In existing sites, the ability to improve upon conventional monitoring techniques
- In planned sites, the ability to detect a leak to within 1 ft^2 (0.1 m^2).

In addition, it was decided to eliminate any techniques from the matrix that were not identified in the literature survey and in consultation with experts in the field as having at least the potential for producing satisfactory results; also, only techniques that did not pose significant risk factors, either to the operators or to the environment, were considered. Thus any technique that could not possibly work without substantial penetration of the site and the liner

TABLE 1. SUMMARY OF CANDIDATE CAPABILITIES

TECHNIQUE	PURPOSE	ADVANTAGES	LIMITATIONS
Mutual Inductance	Measures bulk conductivity. Detects changes of bulk conductivity.	Easy to use in field. Can be used in rough terrain. Easy to detect near surface variations of conductivity. Can be used to either map variations versus horizontal position or in a depth sounding mode. Equipment inexpensive. Penetration depths up to 30 m. Better than VLF wave tilt for shallow sounding. Easy to estimate if variation is deep or near surface. Can be used from the air.	Cannot uniquely detect leak, other information necessary. Repeated measurements necessary to detect changes in response. Conductive overburden shields deeper leaks. Airborne operation reduces sensitivity significantly.
VLF Wave Tilt	Measures bulk conductivity. Detects changes in bulk conductivity. Detects changes in bulk magnetic permeability.	Quite easy to use in field. Can be used in rough terrain. Easy to detect near surface, variations of conductivity. Equipment inexpensive. Equipment can be more sensitive. than mutual inductance technique Can be used from the air. Sensitive to magnetic and electrical variations.	Cannot uniquely detect leak, other information necessary. Repeated measurements necessary to detect changes in response. Conductive overburden will shield deeper leaks. Airborne operations reduce sensitivity significantly. Usually used to map variations versus horizontal position. Susceptible to cultural noise such as power lines, tracks, pipes or fences.

(Continued)

TABLE 1. (Continued).

TECHNIQUE	PURPOSE	ADVANTAGES	LIMITATIONS
Resistivity Schlumberger/Wenner	To measure changes of resistivity either in the horizontal plane (profile mode) or in the vertical plane (sounding mode).	Can be used to map layering versus depth or to detect large resistivitiy variations at a predetermined depth. Reasonably easy to gather data. Equipment inexpensive. Unskilled field crew is satisfactory. Many interpretation curves available.	Deep resistivity variations can be masked by low resistivity layers near the surface. Data acquisition time is long. Sensitive to soil type. Repeated surveys necessary to look for changes. Rapid variations in the topography makes interpretations difficult. Resistivity variations in ground should be at least as large as they are deep or they will not be detected. Susceptible to cultural noise such as pipes, cables, tracks and fences. Equipment relatively inexpensive.
Resistivity Pole-Dipole	To measure changes of resistivity.	Fewer probes need to be moved in field. May be a good way to detect leaks under a conductive overburden.	Interpretation of data often more difficult than Schlumberger or Wenner. Repeated measurements necessary.

(Continued)

TYPING GUIDE SHEET

TABLE 1. (Continued).

TECHNIQUE	PURPOSE	ADVANTAGES	LIMITATIONS
Resistivity Borehole	To measure resistance variations versus depth.	Equipment easily available. Interpretation quite simple. Easy to obtain data in borehole. Can see out from borehole up to ∼ two meters. Adds to other well hole information.	Needs a borehole. Limited penetration range. Sensitive to soil type. Repeated measurements over time necessary. Leachate must be conductive compared to soil.
Resistivity Borehole to Borehole	To measure resistance variations between boreholes.	Measures resistance between boreholes Less affected by site itself.	Needs two boreholes. Repeated measurements to look for changes necessary. Dimensions of leak must be at least 10% the distance between the holes. Leachate must be conductive. Conductive soils will reduce sensitivity of method. Very much at early research stage.
Induced Polarization	To measure induced polarization effects associated with either the liner or the leachate.	Much more sensitive to clay layers than resistivity method. Sounding techniques same as Schlumberger or Wenner techniques. Greater resolution than equivalent resistivity technique.	Equipment more expensive than than resistivity equipment. A conductive waste material will shield the IP measurement.
SP - Surface & Borehole	To measure the potential generated by electrochemical actions in the ground .	Data easily gathered in field. Do not need skilled field crews. Technique sensitive to liquid flow in soils and layers of sediments such as clay layers. Measuring equipment inexpensive. Measurements can be made with other resistivity measurements.	The SP effects can be easily shielded by overlying layers of soil. SP effects must be large and geology simple for interpretation. Interpretation is typically complex due to typically complex geology. Practical measurements of SP due to leachate flow unknown.

(Continued)

EPA Form 2190-4 (4-80)
TYPING GUIDE SHEET

TABLE 1. (Continued).

TECHNIQUE	PURPOSE	ADVANTAGES	LIMITATIONS
HF Pulsed Radar Surface Profiling	To map high frequency electrical variations in the ground such as: Changes in water content, Changes in soil type, Voids either air or water filled, Variations in electrical conductivity. Pipes either metallic or nonmetallic. Frozen or unfrozen interfaces. Soil/bedrock interface.	High resolution mapping in both the horizontal and vertical axis possible. Reasonably easy to transport over surface. Rapid data collection rate. Preliminary data available for initial interpretation in field. Continuous data record available. If geology is relatively simple data is very simple to interpret. Separate transmitting and receiving antennas permit deeper penetration.	High conductive overburden shields deeper reflections. Low penetration in clay soils. Usually needs a vehicle to get equipment near site. High density of information available in complex geologic media requires skilled interpretation. Equipment quite expensive. Works best if antenna in contact with surface. Two antennas more bulky than one. Repeated surveys necessary.
HF Pulsed Radar Velocity Sounding	To determine propagation velocities to each reflector.	Can uniquely determine depth to each reflector. Can determine dielectric constant of each layer and thus help estimate what each layer is physically. Can isolate reflectors from equipment noise.	Requires additional time and effort to carry out each sounding.
HF Pulsed Radar Borehole	To map electrical variations out from borehole.	Can look out from borehole up to tens of meters away. Can look under a dumpsite.	Great care necessary to reduce signal propagation along the borehole itself. Boreholes a possible liability. Plastic casing in boreholes necessary.
HF Pulsed Radar Borehole to Borehole	To map electrical between boreholes.	Greater range between boreholes possible. Transmitter well isolated from receiver. Greater receiver sensitivity possible. Velocity and attenuation measurement possible.	Extra winches and cables needed.

(Continued)

TABLE 1. (Continued).

TECHNIQUE	PURPOSE	ADVANTAGES	LIMITATIONS
Seismic Surface Reflection and Refraction	Determine variations in elastic properties of ground.	Equipment is inexpensive. Can map stratigraphy. Can penetrate through electrically conductive materials. Can detect leachate material in unsaturated soil. Can be used in liquid sites to map clay liner. Can give some estimate of soil type and elastic properties.	Minimum depth often large on the order of many meters. Leak must be above water table to be detected. Leak must have a lateral extent of at least 10% of its depth. Leak must have a significant velocity variation from host medium . Solid waste site will severely limit depth penetration. Repeated measurements over time best.
Seismic Surface to Borehole	Measure variations in seismic wave propagation between the surface and the borehole at various depths.	Only one way propagation considered.	Needs a borehole Needs repeated measurements to monitor change of leak.
Seismic Borehole to Borehole	Measure variations in seismic wave propagation between boreholes.	One way propagation considered. Greater range possible. Measurement affected less by waste site itself.	Needs at least two boreholes. Repeated measurements best. Leak must be in unsaturated soil i.e. above water table. A water table near the bottom of waste sites will severely limit usefulness of method. Leak must be at least 10% in extent compared to borehole separation. Needs additional borehole equipment.

(Continued)

TYPING GUIDE SHEET

TABLE 1. (Continued).

TECHNIQUE	PURPOSE	ADVANTAGES	LIMITATIONS
Acoustic Emission	To monitor sounds emitted as leachate flows through the soil.	May be used in a liquid site. Can put receiver near bottom of pond and map noise versus location. Basic field equipment inexpensive. May be useful for detecting and locating area where a large leak is occurring. May be pre-installed in planned sites.	Needs a borehole or pipe put into solid dumpsite. Background noise from dumpsite significant. Needs expensive data reduction equipment to be practical. Must monitor continuously.
DC Grid	To detect a leak in the liner by letting a wire corrode.	Precise location of a leak possible if cross wires in the grid break. Wires may be made that are particularly sensitive to leachate type. Measurement equipment inexpensive.	Must be emplaced with liner before waste is added. Must survive for the life of the site unless leak occurs. Mechanical stress may cause wire to break. If only one wire breaks, then position still not known. Once wire is broken it cannot be used again. Many wires necessary.
TDR Grid	To detect a leak under a liner by observing a change in high frequency electrical properties due to leachate.	Precise location of leak is possible. Leachate flow between the wires can be detected. Wires can be insulated so that they do not corrode too rapidly. Wires may be run in one orientation only; i.e. cross wires may not be necessary. Data can be easily interpreted by computer. Response from broken wire different than response from leachate material.	Wires must be emplaced with liner when site is built. Must survive for life of the site. Mechanical stress may break wire. If wire breaks the ends of wires can still be used. Spacing between wires unknown. Repeated measurements with time needed. Measurement equipment needs to be developed. Resolution about equal to wire spacing.

EPA Form 2350-4 (4-80)
TYPING GUIDE SHEET

were rejected for further consideration. This limitation severely reduces the number of techniques that can be used in existing sites and also the probability of success for detecting leaks under the waste site itself.

MATRIX STRUCTURE AND OPERATION

To be useful, a ranking matrix requires the development and use of an evaluation rationale that leads to a meaningful ordering of the candidate methodologies in terms of their capability to meet the desired objectives. Thus a multi-staged procedure was followed in order to achieve a useful format for the matrix itself, and to select and define the parameters used for assessment of each candidate. At each step in the process, a Board of Consultants reviewed and amended the program results. (See Board of Consultants, Appendix C.)

Step One

The matrix itself was formatted. Table 2 displays the completed matrix. Parameters are listed across the top of the matrix, and each major subject heading is broken into a number of factors which further define the parameter. Thus the major heading SENSITIVITY is further defined as soil type, waste type, and cultural noise. The candidates are listed along the left margin of the matrix. Finally, the score in each cell of the matrix applies to one objective and one candidate. Each cell thus represents a judgment as to how well the candidate meets the objective. The candidates are scored by summing the matrix cells. Note that no attempt has been made to make the scores fully quantitative, since the information to provide such an assessment is lacking without laboratory or field applications.

Step Two

The parameters themselves were selected and defined. This allows a process in which the various judgments can be made in an organized fashion, clarifying the choices in the mind of the individuals executing the matrix. Although this process does not eliminate subjective judgments, it confines each judgment to a set of limited choices.

Step Three

The matrix was executed. A conference, moderated by the Program Manager and attended by all members of the research team and the EPA Technical Monitor, was held in order to thoroughly review and discuss weights and ratings. Final weights for each technical parameter and sub-parameter were set at this point, and then each candidate methodology was assessed. Once these decisions were finalized, each technique was independently rated. This meeting provided interactive discussion, which lent confidence to the final matrix results.

TABLE 2. MULTIPLE OBJECTIVE RANKING MATRIX WITH WEIGHTS

Candidate Methodologies	Operational Parameters			Sensitivity			Technical Factors								Data Reduction				Impacts			Economic Factors								System Capabilities			
	Surface/Borehole	Inside/Outside/Both	Applied/N-A in Field	Soil Type	Waste Type	Cultural Noise	Range	Resolution	Lateral Extent	Vertical Extent	Threshold Sensitivity	Contrast	Flow Direction	Precision	Data Acquisition Time	Interpretation Time	Data Reduction Time	Ancil. Data Reduction Equip.	Impact PH & Safety	Site Disruption	Site Safety & Liability	Capital Cost	Installation Cost	Operation - Labor	Operation - Materials	Operation - Maintenance	Data Reduction-Ancil. Equip.	Data Reduction - Labor	Data Reduction - P M & S	Operator Skill	Portability	Survivability	Availability
Group Weights				9			10								8				5			2								1			
Parameter Weights				2	2	1	5	4	2	2	4	4	3	3	5	4	2	1	4	2	5	5	5	5	3	3	3	5	3	4	1	5	3
Mutual Inductance	S	B	A	1	1	2.5	3	2	4	3	3	4	3.5	3	2.5	2.5	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
VLF Wave Tilt	S	B	A	1	1	1.5	3	2	4	3	3	4	3.5	3	2.5	2.5	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
EM/HF Pulsed Surface	S	B	A	1	1	3	3	4	4.5	4	3	4	4	3	2	2.5	2	3	3	3	3	2	3	2	2.5	2.5	2	2	2	2	2	3	2
EM/HF Pulsed Borehole	B	O	N	1	1	3	4	3	4.5	4	3	4	4	3	2	2.5	2	3	3	3	3	2	2	2	2.5	2.5	2	2	2	2	2	3	2
CW/HF Surface	S	B	N	1	1	3	2	3	5	4	3	3.5	4	2.5	2	1	1.5	1.5	3	3	3	2	3	2	2	2	2	1.5	1.5	2	2	3	1
CW/HF Borehole	B	O	N	1	1	3	4	3	4	3	3	4	3	3	2	1	1	2	3	3	3	2	2	2	2	2	2	1.5	2	2	2	2	1
Resistivity Schlum/Wen	S	B	A	1	1	2	5	1.5	3.5	3	3	4	3.5	4	2	2	2	2.5	3	2	3	3	3	2	3	2.5	2.5	2	2.5	2.5	3	3	2
Resistivity Pole-Dipole	S	B	A	1	1	2	5	3	3	2	3	4	4	4	2	2	2	2.5	3	2	3	3	3	1.5	3	3	2.5	2	2.5	2	3	3	1.5
Resistivity Borehole	B	O	N	1	1	2.5	2	1	3.5	4.5	1	4	4.5	4	2.5	2.5	2.5	3	3	3	3	3	2	2.5	3	3	3	2.5	2.5	2	2.5	3	2.5
Resistivity Cross-Hole	B	O	N	1	1	2.5	5	1	3	3	3	4	4	4	2.5	2.5	2.5	3	3	3	3	3	2	2.5	3	3	3	2.5	2.5	2	2.5	2.5	2.5
Induced Polarization	S	B	N	1	1	2	5	1.5	2	3	3	4	3	3	2	2	2	2	3	2	3	2	3	2	3	2	2	2	2	2.5	2.5	3	2
SP Surface	S	B	A	1	1	1.5	3	3	3	2.5	3	2	4	1.5	2.5	2.5	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2
SP Borehole	B	O	N	1	1	1.5	2	1	3	5	1	3.5	4	2	2.5	2.5	3	3	3	3	3	3	2	3	3	3	3	3	3	3	3	3	2
Seismic Surface	S	B	A	1.5	2	3	5	3	4	4	3	4	3.5	4	2	2	2	2	3	3	3	3	3	2	2.5	3	2	2	2	3	3	3	3
Seismic Surf. to Borehole	S&B	B	N	1.5	2	3	5	3	4	4	3	4	3	3.5	2	2	2	2	2.5	2.5	2.5	3	2	2	3	3	2	2	2	3	1.5	3	3
Seismic Cross-Hole	B	O	N	1.5	3	3	5	3	4	3	3	4	3	3.5	2	2	2	2	2.5	2.5	2.5	3	2	2	3	3	2	2	2	3	2.5	3	3
AE Surface & Borehole	B	1	N	1	1	2	3.5	2	-	-	4.5	3	3.5	3.5	2.5	2.5	3	3	2	2	2	3	3	3	3	3	3	3	3	2.5	3	3	2
DC Grid	-	-	N	1.5	2	3	5	3	-	-	4	4	-	3.5	2	3	2.5	2.5	3	3	3	3	2	2	3	3	3	3	3	3	3	2	2.5
TDR Grid	-	-	N	1.5	2	3	5	4	5	5	4	4	-	3.5	2	2	2	2	3	3	3	3	2	2	3	2.5	2.5	2	2.5	2	3	3	2

3-Low
2-Med.
1-High

5-Excel. 2-Poor
4-Good 1-Not Useful
3-Fair

3 - Low
2 - Mod.
1 - High

EPA Form 2350-4 (4-80)
TYPING GUIDE SHEET

DEFINITION OF TERMS USED IN MATRIX

The definition of terms and the rationale presented for final execution of the ranking matrix are discussed below. Each candidate methodology selected for the ranking process was assessed according to these criteria.

Operational Parameters

The following parameters define the operational limitations and characteristics of the candidate technology. These parameters are intended primarily as guides to the applicability of the candidate to a particular landfill site rather than as a means of judging the absolute potential of the candidate.

Solid Liquid Waste Impoundment--

Liquid impoundment sites are generally more homogeneous in makeup than solid sites. Thus, many techniques that are not useful in solid sites may have application to liquid wastes. It is also likely to be easier to place sensors into liquid wastes than into solids. In addition, a leak in a liquid site will generally have greater volume and thus be less discrete and more readily detectable than leachate leaking from a solid waste site.

Surface/Borehole/Airborne--

This parameter defines the mode of operation of the candidate. Surface techniques may generally be expected to be useful at either existing or new waste impoundments while in-situ systems may require the emplacement of transducers within or beneath the site during construction. In many cases, a candidate may operate in both modes, and this parameter is used to distinguish between modes. Electrical resistivity may be used from the surface, in which case it is easy to change the survey so as to investigate more closely suspect areas, or electrical resistivity may be used in-situ by pre-placing electrodes. Greater resolution is thereby obtained, since the sensors are nearer the target, but less flexibility is possible since the probe locations are fixed. In some cases, the designation "surface/in-situ" is arbitrary. Acoustic emission using waveguides is defined as a surface system, while AE monitoring from boreholes is defined as an in-situ system.

Destructive/Non-destructive--

Does the candidate technique require excavation of the impoundment site or other physical disruption? Generally, non-destructive techniques are preferred.

Inside/Outside/Both--

Does the candidate operate completely within, outside or across the membrane?

Applied/Not Applied in Field--

Has the system been used in actual field application to detect leachate presence or flow from impoundment sites, or is it conceptually applicable with the possibility of practical field application.

Sensitivity

This parameter may be used to determine whether a particular candidate should be used at a particular site and also to determine the general universality of the candidate. If a candidate may be used under all site conditions, it will generally be more valuable than one that may not, or that will require radically different operational systems under different site conditions. The following values are assigned to these parameters:

1. The candidate will be strongly influenced by conditions found at different sites, and may require different operational methods, or may be useful in some sites and not in others.
2. The candidate will be only weakly affected by the range of conditions likely to be found in waste impoundment sites.
3. The candidate operates equally well under all conditions ikely to be found in waste disposal sites.

In general, it is intended to isolate the possible sensitivity of the candidate from the sensitivity of the leak itself. These parameters should be highly connected, since they may be expected to be used for the selection of monitoring techniques for particular sites as well as a tool for the identification of candidates worthy of additional development by the Environmental Protection Agency.

Soil Type--

Is the candidate operation not at all, weakly, or strongly affected by the type of soil?

Waste Type--

Is the candidate operation not at all, weakly, or strongly affected by the type of waste found in the site?

Cultural Noise--

Do particular types of cultural noise exist that will affect the operation of the candidate, and what is the potential severity? Identify the forms of interference and how it may be reduced. Examples of cultural noise would be:

- For AE monitoring of seepage, the mechanical background noise associated with the operation of heavy equipment on or off site, at the interference may be reduced by working in-situ and using frequency filtering to eliminate cultural noise while still hearing the seepage noise.
- For electrical resistivity or self-potential, the ground currents produced by certain industries, electric trains, and items such as conductive fences or utility conduits.

Leak Detection--

Can the candidate detect a leak point or detect leachate plume?

Technical Factors

These factors are concerned with the ability of the candidate, after full development, to detect and locate leaks. Where possible, previous applications of the candidate should be used as checkpoints on the assignment of satisfaction coefficients, but it must not be assumed in such a case that the previous application of the technique in fact represents the full development of the technique. We are interested in theoretical limits as they may be approached by additional Phase II and Phase III development efforts. The range of satisfaction coefficients for these technical efforts is:

5 - Excellent
4 - Good
3 - Fair
2 - Poor
1 - Not Useful (None)

Range--

At what distance from the monitoring point can the candidate detect a leak?

5 - Greater than 30 meters
4 - 10-30 meters
3 - 3-10 meters
2 - 1- 3 meters
1 - Less than 1 meter

Resolution--

How closely will the candidate locate the X-Y coordinates of a leak in the liner. Approximate error limits are taken as:

5 - 30-100 cm
4 - 1-3 meters
3 - 3-10 meters
2 - 10-30 meters
1->30 meters

Lateral Extent of Escaped Leachate Plume--

How closely can the candidate map the lateral extent of the escaped leachate plume? Approximate error limits are taken as:

5 - 3 meters
4 - 10 meters
3 - 30 meters
2 - 100 meters
1 - 300 meters

Vertical Extent of Escaped Leachate Plume--

Similarly, it is important to be able to define the vertical location of the escaped leachate. Values of error are approximately:

5 - 30 cm
4 - 1 meter
3 - 3 meters
2 - 10 meters
1 - 30 meters

Threshold Sensitivity--

Threshold sensitivity is defined in terms of the potential damage already incurred at the time the candidate may be expected to identify the leak. Levels are:

5 - Leachate has not yet begun to escape from the site, but the liner has been distressed or otherwise disturbed so that a leak may be expected.

4 - Leachate flow has started through the liner.

3 - Soil beneath the waste impoundment is saturated, but the leachate plume has not contacted the ground water.

2 - The leachate plume has contacted the ground water.

1 - The leachate plume has traveled out from under the site itself, but is still within the range of conventional ground-water monitoring techniques.

Flow Direction--

It may be useful to determine the direction of leachate flow underground. This would combine with the factor "lateral extent of leachate plume" to increase confidence in the results of the leak detection system. Approximate levels of the satisfaction coefficients are:

5 - The leachate flow field is fully defined, including the separation of components that travel at different velocities.

4 - Flow direction is known to perhaps a half a radian.

3 - Flow direction is known to be north, south, east, or west.

2 - Flow direction is only weakly determined by the candidate technique.

1 - The candidate is totally insensitive to flow direction.

Precision--

Note the formal definitions:

accuracy = absolute nearness to truth

precision = apparent nearness to truth; repeatability of measurements.

Accuracy may be known only if a powerful and independent measurement may be made of the quantity under consideration, or may be estimated if a formal relationship exists between the quantities being measured:

given that:

$$A = f(X,Y,\ldots,Z)$$

then the standard deviation is:

$$\sigma_A^{\,2} = \left(\frac{\partial A}{\partial X}\right)^2 \sigma_X^{\,2} + \left(\frac{\partial A}{\partial Y}\right)^2 \sigma_Y^{\,2} + \cdots + \left(\frac{\partial A}{\partial Z}\right)^2 \sigma_Z^{\,2}$$

Precision, on the other hand, may be estimated on the basis of data scatter, and the assumption that the quantity being measured is somehow related to the quantity of interest. For our purposes, we consider that a precise system will give the same data on two subsequent surveys if no changes in the waste impoundment integrity have occurred in the intervening time period. Assigned levels are:

5 - The measurement is reliable under all circumstances to identify a leak with a single measurement.

4 - The candidate has been used, and its ability to obtain measurements has been shown to be reliable and repeatable.

3 - The reliability of measurement by the candidate should be compared with other monitoring systems as well as events known to have taken place at the site to build confidence.

2 - The candidate indicates that something has probably occurred, and the other measurements should be taken to determine just what.

1 - Subtle data reduction is required to determine that something is occurring. The candidate should be considered more as an alarm than a diagnostic tool.

Data Reduction and Availability

The factors discussed in Appendix A deal with the general characteristics of the candidate hardware and its operation. In the same fashion, this section deals with the candidate software.

Data Acquisition Ease--

How easy is it to get additional data points. Our concern is with raw data only, not interpretation. Levels are:

3 - Very easy. One unskilled person can gather data.

2 - Moderate. One skilled or two or more unskilled persons required to gather data.

1 - Difficult. The candidate may require a crew of three or more skilled operators.

Ease of Data Interpretation--

This factor is concerned with the level of skill, experience and judgment required for data interpretation.

3 - Moderate. Interpretation requires familiarity with the candidate and its use.

2 - Difficult. The use of expert interpretation is necessary because of the difficulty. Typically this work is done by skilled specialists, perhaps retained as consultants because of the high level of expertise necessary.

1 - Very complex. May require computer program.

Data Reduction Time--

How quickly can the data be reduced so that a check may be made against other systems, suspect leaks may be evaluated, and additional data obtained.

3 - Fast. Cursory evaluation in the field is sufficient to determine whether a more detailed survey should be conducted.

2 - Moderate. The data are returned to the laboratory for detailed evaluation and comparison with previous surveys. Typically, response time of only a few days is required.

1 - Slow. Detailed analyses of the data are required before confident statements can be made about it.

Need for Ancillary Equipment--

What level of ancillary equipment and specialized material are needed for data reduction?

3 - None. The data are reduced using, at most, hand calculators, graph paper, and such items as may typically be found in an engineering office.

2 - Moderate. One probably will need a microprocessor and simple software for data reduction.

1 - Extensive. Access to a mainframe computer and specialized programs is required. Alternatively, laboratory tests of some considerable sophistication may be needed.

Impacts

Public Health and Safety--

3 - No potential impact.

2 - Potential for impact exists, but is small.

1 - Potential for severe impact or high probability of less severe impact.

Site Disruption--

3 - No disruption to site operations.

2 - Minimal interruption to site operations.

1 - Possible total disruption of operations, small possibility of disturbance to site integrity.

Note: Does not include any impact to site operation resulting from false positive leak detection results.

Site Safety and Liability--

3 - No possibility of liability or damage to site.

2 - Small possibility that site integrity will be compromised, but can be avoided by maintenance of simple quality control/quality assurance procedures.

1 - Possibility of liner penetration and subsequent major liability problems.

Economic Factors

Life cycle costs were broken down into capital cost of the candidate system; operational costs for installation of any special sensors; and for the labor, materials, and maintenance of the candidate in the field; and data reduction costs.

Capital Cost--

What investment is required to install the candidate? This would typically be shown as a capital cost amortized over the expected lifetime of the equipment.

3 - 0-$10,000

2 - $10,000- 50,000

1 - In excess of $50,000

INITIAL INSTALLATION

3 - 0-$10,000

2 - $10,000-50,000

1 - In excess of $50,000

Operational Costs - Labor--
Does operation of the candidate require a large crew of highly skilled individuals, or can it be operated by a few individuals.

3 - Low. One unskilled operator.

2 - Moderate. Requires a small crew, or a single highly skilled operator.

1 - High. Requires a crew of five or more, at least one of whom is highly skilled, the others having experience with the system or is being professionally trained.

Operational Costs - Materials--
3 - Low. Materials used in the field limited to notebooks, paper, perhaps batteries for the hardware.

2 - Moderate. May require support of heavy vehicles, or use expensive test materials.

1 - High. Rental of chartered aircraft.

Operational Costs - Maintenance--
3 - Low. The candidate electronics may require annual calibration, and sensors have high survivability.

2 - Moderate. The system is a bit delicate, and is best calibrated in the laboratory before use. Frequent return to the manufacturer is necessary. Sensors require frequent replacement.

1 - High. The equipment is specialized, delicate, and requires constant and expert nursing to stay in operation. Calibration and checks are required prior to each survey to ensure that the system works.

Data Reduction Costs - Ancillary Equipment--

3 - Low. No equipment required other than that expected to be found in any engineering office.

2 - Moderate. Requires small computational facilities, samples sent out to commercial laboratory for analysis.

1 - High. Mainframe computational power, extensive testing.

Data Reduction Costs - Labor--

3 - Low. Data easily reduced by graduate student.

2 - Moderate. Requires experience and judgment.

1 - High. Requires expert to reduce data and interpret results.

Data Reduction Costs - Materials and Services--

3 - Low. No special materials required other than paper, etc.

2 - Moderate. May require some data reduction, statistics, laboratory testing, etc.

1 - High. Requires expensive tests in external laboratory and/or access to mainframe computer and services.

System Capabilities and Characteristics

The factors listed in this section relate to the nontechnical characteristics of the candidate when used as a leak detection system. Three levels of satisfaction are possible, typically identified as low, moderate or high.

Required Level of Operator Skill--

It is desired that highly skilled operators not be required for operation of the candidate leak detection system. The levels are:

3 - Low. The instrument is easily operated.

2 - Moderate. Training and some experience with the candidate are required to enable the technician to operate the candidate.

1 - High. The candidate should be operated only by one highly trained who has considerable experience with the candidate and the advanced technical and theoretical training required to thoroughly understand the candidate and its operation.

Portability--

3 - Highly portable. Can be carried by hand.

2 - Moderate. Requires a light vehicle, such as a sedan, jeep or light van.

1 - Low. Mobilization of the system requires planning for heavy vehicles, or trailers for support systems.

Survivability--

Survivability is related primarily to the integrity and ruggedness of those portions of the candidate that may be placed in-situ and are not easily replaced. Clearly, a surface candidate has high survivability unless the instrument itself is highly delicate and difficult to replace if damaged. Assigned levels are:

3 - High. Sensors may be expected to last for the life of the waste site with no attrition.

2 - Moderate. With care, lost sensors will not be a major problem, but emplacement of redundant sensors would avoid the bother of replacement.

1 - Low. Great effort will be required to maintain the candidate in operating condition.

Availability--

Can the candidate be easily obtained from commercial sources, or must special designs be implemented, or must one acquire the candidate and its operation only from unique sources? Assigned levels are:

3 - High availability. Readily available; no particular skill required for use.

2 - Moderate availability. Available on the market, but models must be surveyed to determine suitability for project.

1 - Limited availability. The system is manufactured or implemented by a unique source. Should that source fail, or become unrealistic in their terms, assistance of expert consultants to design/manufacture a replacement system (or services) may be required.

WEIGHTING FACTORS

Weighting factors were selected by the best judgment of the total project team. It is clear that some of the parameters are more vital for success than other parameters; therefore to account for this a weighting scale was devised. The weights as shown in Table 3 were chosen on the basis of importance within each of the six main groups. For example under "Technical Factors," range was considered to be the most important, and was given a weight of 5, followed closely with a weight of 4 for resolution, threshold sensitivity, and contrast. Flow direction and precision were next in importance, with a weight of 3, followed lastly with a weight of 2 by the capability of the techniques to measure the vertical and the lateral extent of the leak. Thus, if a technique had a very large penetration range and could detect the expected properties of the leak then it was given a higher rating compared to a technique with similar capabilities, but very limited penetration range. Similar considerations were made when determining the weights in each of the other five groups of parameters.

All of the groups of parameters were normalized so that some of the groups would not be given greater weight or significance because there are more parameter columns within the group. Note for example that the "Impacts" could receive a maximum score after being given the individual parameter weights of 33 [(3x4)+(3x2)+(3x5) = 33] whereas the "Economic Factors" could receive a score of 96 [(3x5)+(3x5)+(3x5)+(3x3)+(3x3)+(3x3)+(3x5)+(3x3) = 96]. The first number in the curved parenthesis is the maximum parameter score and it is multiplied by the parameter weight and this is then added to the next maximum parameter score multiplied by the parameter weight and so on. The maximum group parameter score for each of the groups were as follows:

Sensitivity	15
Technical Factors	135
Data Reduction	36
Impacts	33
Economic Factors	96
System Capabilities	39

In order to reduce the bias in the final answer each of the parameter weighted scores was normalized within the parameter groups. First, since the Technical Factors were rated on a 1 to 5 scale rather than a 1 to 3 scale we multiplied the Technical Factors total by 3/5 bringing the maximum score for this group parameter to 81. This normalization was carried out by multiplying each of the summed group parameter scores by the maximum total score of 300 obtained for all of the parameter groups and then dividing by the maximum possible score for the group parameter in question. For example, for the "Impacts" group the sum of each of the parameter weighted score was multiplied by the maximum total score of 355 and divided by the maximum score for the Impacts group of 34 reducing to 10.4. The normalizing factors for each of the parameter weighted group scores is shown below.

Sensitivity	20.0
Technical Factors	3.7
Data Reduction	8.3
Impacts	9.1
Economic Factors	3.1
System Capabilities	7.7

A logical set of weights could then be applied to each of the groups of parameters.

The "Technical Factors" group was considered to be the most significant group and then the "Sensitivity" group the next most significant, closely followed by the "Data Reduction" group. These groups are most important because they determine whether or not the technique can be used to detect a leak at an impoundment site. Each of the group weights is shown in the first row under group weights of Table 2.

A weighting is applied to the score of each group of parameters. No special principle dictates the curve--it is the result of the weights applied after the practical significance of each group of parameters was considered by experts comprising the project team.

It is interesting to note that about 77 percent of the total weighting is given to geophysical factors, 14 percent to site and safety factors, and 9 percent to economic factors and system capabilities. Though the group weights were not determined using any sort of percentage criterion, the percentage weights shown seem very reasonable and acceptable.

The least expensive and lightest detection technique is useless unless it can detect the leak in the ground and the data can be satisfactorily interpreted with no risk to people on the site. Thus "technical factors, "sensitivity," and "data reduction" received the greatest weights. "Impacts" are also important and get the next highest score. "Economic factors" and "system capabilities" get the lowest weight because their total costs are minimal compared to the damage caused by contaminants in the ground water. If an expensive and cumbersome system will detect a leak in an impoundment liner then the financing can be obtained easily compared to the cleanup and reclamation costs necessary after a leak enters the ground water.

All the values given on a relative scale of 1 to 10; 10 being the maximum value obtainable in each parameter group. A low rating in a high weighted sub-parameter such as "range" in "technical factors" will decrease the score more than if a low value was obtained in either vertical or lateral extent parameters.

SIGNIFICANCE OF THE VALUES IN THE MATRIX

It is necessary to consider the significance of the values shown in the matrix. Initially, in all of the groups the ratings were given on a scale of 1 to 3, except in the "technical factors" group, which was rated on a scale of 1 to 5. These coarse scales were decided upon since any larger scales would have been meaningless because of the variability of the factors involved and the subjectivity in rating the techniques. Thus the values in the matrix are only significant to ± 1.5 in all cases except in "technical factors," which are significant to ± 1.0. The average of all factors column is significant to ± 1.5. The decimal values were rounded to the nearest .5. The shading is used to help indicate within the technical parameters and the average of all parameters columns which scores are greater or less. The scale used for the shading is shown on the matrix in Tables 3, 4, and 5. The darker the shading the higher the score. For example, it can be seen that the HF pulse techniques tend to have higher scores in the technical parameters than do the SP techniques. The scores in the "impacts," "economic" and "system capabilities" parameters are not shaded because of their low overall weighting factors.

TYPING GUIDE SHEET

TABLE 3. APPLIED METHODS SUMMARY OF RANKING MATRIX

Technique	Technical Factors	Sensi-tivity	Data Reduction	Impacts	Economic Factors	System Capabil-ities	Average of all Parameters
Significance of Values	± 1	± 1.7	± 1.7	± 1.7	± 1.7	± 1.7	± 1.5
Mutual Inductance	6.2	4.3	8.4	10.0	10.0	10.0	7.1
VHF Wave Tilt	6.1	3.7	7.4	10.0	10.0	10.0	6.7
HF Pulse Surface	7.2	4.7	7.5	10.0	7.6	6.8	7.1
Resistivity Schlumberger/ Wenner	6.9	4.0	6.3	9.4	8.5	8.6	6.6
Resistivity Pole-dipole	7.1	4.0	6.3	9.4	8.2	7.9	6.5
SP Surface	5.3	3.5	8.4	10.0	10.0	9.2	6.6
Seismic Surface	7.5	4.0	6.7	10.0	8.6	9.9	6.9

▓	▒	░	☐
8.1-10	6.1-8	4.1-6	Less than 4.1

TYPING GUIDE SHEET

TABLE 4. R&D METHODS SUMMARY OF RANKING MATRIX

Technique	Technical Factors	Sensitivity	Data Reduction	Impacts	Economic Factors	System Capabilities	Average of all Parameters
Significance of Values	± 1	± 1.7	± 1.7	± 1.7	± 1.7	± 1.7	±1.5
Seismic Surface to Borehole	7.4	4.0	6.7	9.2	7.7	9.9	6.7
Seismic Borehole to Borehole	7.3	4.7	6.7	9.2	7.7	9.9	6.8
HF Pulse Borehole to Borehole	7.2	4.7	7.5	10.0	7.2	7.7	7.1
Resistivity Borehole to Borehole	6.5	4.4	6.8	10.0	8.7	8.0	6.8
Resistivity Borehole	5.6	4.3	8.1	9.8	8.8	8.6	6.7
Induced Polarization	6.6	4.0	6.7	9.4	7.4	8.3	6.4
CW/HF Borehole to Borehole	6.8	4.0	5.0	10.0	6.1	5.9	6.1
CW/HF Surface	6.2	4.0	5.1	10.0	6.6	7.2	6.0
SP Borehole	4.8	3.8	8.4	9.5	9.5	9.2	6.4
Planned Sites							
TDR Grid	8.5	6.7	6.8	10.0	7.9	8.0	7.8
DC Grid	7.2	6.7	8.1	10.0	8.6	8.3	7.8
Acoustic Emission	6.1	4.6	9.8	6.8	9.7	8.7	6.8

▓	▨	░	☐
8.1-10	6.1-8	4.1-6	Less than 4.1

TABLE 5. SUMMARY OF RANKING MAXTRIX

Technique	Technical Factors	Sensitivity	Data Reduction	Impacts	Economic Factors	System Capabilities	Average of all Parameters	Applied Not Applied
Significance of Values	± 1	± 1.7	± 1.7	± 1.7	± 1.7	± 1.7	± 1.5	
Mutual Inductance	6.2	4.3	8.4	10.0	10.0	10.0	7.1	Applied
VLF Wave Tilt	6.1	3.7	7.4	10.0	10.0	10.0	6.7	Applied
HF Pulse Surface	[illegible]	4.7	7.5	10.0	7.6	7.8	7.1	Applied
HF Pulse Borehole to Borehole	[illegible]	4.7	7.5	10.0	7.2	7.7	7.1	Not Applied
Seismic Surface	7.9	4.0	6.7	9.2	8.6	9.9	6.7	Not Applied
Seismic Surface to Borehole	7.4	4.0	6.7	9.2	7.7	9.9	6.7	Not Applied
Seismic Borehole to Borehole	7.3	4.7	6.7	9.2	7.7	9.9	6.8	Not Applied
Resistivity Borehole to Borehole	6.8	4.4	6.8	10.0	8.7	8.0	6.8	Not Applied
Resistivity Pole-dipole	7.1	4.0	6.3	9.4	8.2	7.9	6.5	Applied
Resistivity Schlumberger/Wenner	6.9	4.0	6.8	9.4	8.5	8.6	6.6	Applied
Resistivity Borehole	5.6	4.3	8.1	9.8	8.8	8.6	6.7	Not Applied
Induced Polarization	6.6	4.0	6.7	9.4	7.4	8.3	6.4	Not Applied
CW HF Borehole to Borehole	6.8	4.0	5.0	10.0	6.1	5.9	6.1	Not Applied
CW HF Surface	6.2	4.0	5.1	10.0	6.6	7.2	6.0	Not Applied
SP Surface	5.3	3.5	8.4	10.0	10.0	9.2	6.6	Applied
SP Borehole	4.8	3.8	8.4	9.5	9.5	9.2	6.4	Not Applied
TDR Grid	8.5	6.7	6.8	10.0	7.9	8.0	7.8	Not Applied
DC Grid	7.2	6.7	8.1	10.0	8.6	8.3	7.8	Not Applied
Acoustic Emission	6.1	4.5	9.8	6.8	9.7	6.7	6.8	Not Applied
NOT GEOPHYSICAL								
Piezometer	3.9	N/A	5.8	8.3	8.1	8.7	6.4	Applied
Lysimeter	4.9	N/A	6.8	8.3	8.1	8.7	6.7	Applied

9 ■ 8.1-10 7 ▨ 6.1-8 5 ░ 4.1-6 ☐ Less than 4.1

The last column in Table 5 indicates whether or not references exist in the literature of the technique being applied in the field to detect leaks or leachate plumes. A discussion of the results of the matrix follows.

MATRIX RESULTS

The first column in Figure 5 to be studied is the "average of all parameters" column. It is noted that all the values tend to group around 6.5 (±0.4) with the exception of the two grid techniques which are about 8. There is clearly no significant variation among the techniques considered here when the averages of all the parameters are compared. This is only surprising until the initial assumptions made are considered. Two assumptions were made:

- The first assumption was that the candidate technique had to be able to detect leachate materials out from the boreholes or to a depth of greater than 30 cm depth.
- The second assumption was that the candidate technologies were only considered in hypothetical situations where they had a probability of working. There are always situations where each of the techniques will not work and the exercise would become futile.

Considering the above assumptions the value of the average of all parameters is neither surprising nor unreasonable. The technical parameters have about 77 percent of the total weight, and considering the assumptions, then a two-thirds rating in the matrix is acceptable. It is now worth considering the technical and sensitivity parameters in some detail.

Note that all of the techniques are very sensitive to both soil type and waste type. All the techniques have an average value of about 4 (±1.2). This value indicates there is a large probability that none of the techniques will work in many of the situations found in a typical waste site. The two grid techniques are less sensitive to the site conditions. These techniques do not require measurements be taken through the waste materials; they are only feasible for planned sites where optimum conditions can be selected for operation of the techniques.

All of the data reduction parameters tend to group around 6.5 (±2.5). Once again only relatively simple data interpretation using each technique was considered. It is clear that good data is necessary and only then will good data reduction techniques make the difference between the success or failure of the survey.

It is interesting to note that all the values in the "impacts" group have very high ratings. This is because only techniques that did not have any significant risk factors either to the operators or the waste site were considered. The lower values were given if holes for short rods in or boreholes near the site were necessary. Obviously if there is any risk to the operator or the site then the technique is impractical. This limitation severely reduces the number of techniques that can be used and also the probability of success for detecting leaks under the waste site itself.

All of the values in the "technical factors" group for existing sites tend to have values of about 6.5 (±0.9). This appears to be discouraging at first and certainly indicates the difficulty in using any geophysical or other techniques for monitoring or detecting leaks from an existing waste site. It is clear that no one technique stands out as superior for detecting leaks in existing sites, and thus points to the need for a study of this type.

This matrix makes it abundantly clear that a composite of techniques must be used to solve this complex problem, particularly at existing sites. All the techniques are sensitive to the different electrical properties of a leachate in the host medium except the seismic and acoustic emission techniques, which are sensitive to the elastic properties and density changes caused by a leak or the acoustic emission from the fluid flow from a leak. Thus exercised in combination, a composite geophysical survey can be designed to monitor a complex of materials properties, thus enhancing confidence in the survey results.

Note that those techniques evaluated for planned sites received overall higher scores. This reflects the reality of the problem, as reflected in both the literature survey and the matrix results. It will be easier to design for liner integrity and performance monitoring programs when the design is included and planned for at the conception of a total waste disposal program. In addition, conventional monitoring techniques were evaluated, in an attempt to formulate a baseline score against which to measure the other candidate techniques. Note that despite the problems associated with geophysical techniques, they still hold out greater promise of success under optimum site conditions than do the conventional monitoring methods. Leak detection at existing lined sites is, and will continue to be, more problematical. However, skillful use of the techniques described herein, should lead, in many cases to leak detection prior to the occurrence of extensive ground water contamination.

Each candidate methodology is summarized according to its capabilities in Table 1. These tables can be used as a reference guide to each technique and its ideal field application.

SECTION 5

APPROACHES TO LEAK DETECTION AT HYPOTHETICAL, EXISTING AND PLANNED WASTE IMPOUNDMENT SITES

The results of the state-of-the-art review and the multiple objective ranking matrix indicated certain possible successful approaches to the problem of leak detection at both existing sites and at waste impoundments that might be constructed at some future date. These potential problem approaches are discussed below. Due to the degree of difficulty and variability of possible solutions to problems at existing and planned lined sites, each hypothetical situation is treated separately. In addition, each candidate leak detection methodology identified during the state-of-the-art review, assessed in the ranking exercise is briefly reviewed in terms of its particular application to the problem. Flow charts, tailored to each hypothetical site situation are included, to aid in designing a comprehensive leak detection program. Properties of importance to successful site assessment and leak detection in both existing and planned sites are also discussed.

SITE PROPERTIES

Site properties of importance to leak detection are essentially similar in both existing and planned lined waste disposal facilities, and require a thorough review before a leak detection program can be finalized. Relevant properties are summarized below and the sensitivities of candidate methodologies to specific site properties are listed in Table 6.

Properties of Area Under Study--

FACTORS

A. Geographical

1) Location of waste material in site
2) Areal extent of waste site
3) Depth of waste site
4) Surface topography
5) Outline of leachate plume

B. Geological

1) Complexity of geology in area
2) Stratigraphy of soil
3) Depth to bedrock
4) Liner material

TABLE 6. SENSITIVITY OF CANDIDATE METHODOLOGIES TO SITE PROPERTIES

METHOD	FACTORS*	REMARKS
Surface Techniques		
Mutual Inductance	A. 1),2),3),5) B. 1),2),5) C. 1) F. 1)[i,ii,iii,a],3)	Light, portable, easy to use and inexpensive
VLF Wave Tilt	A. 1),2),3),5) B. 1),2),3),5) C. 1) F. 1)[i,ii,iii,a],3)	As above, might see deeper but not as shallow
HF Pulse	A. 1),2),3),5) B. 1),2),3),4),5) C. 1) F. 1)[i,ii,iii,b]	High reduction over surface tens of meters, much less in conductive ground, expensive, non-portable, interpretation advanced
Resistivity Profiling and Sounding	A. 1),2),3),5) B. 1),2),3),5) C. 1) F. 1)[i,ii,iii,a],2)	Light, portable, inexpensive
Resistivity Pole-dipole	A. 1),2),3),5) B. 1),2),3),5) C. 1) F. 1)[i,ii,iii,a],2)	Light, portable, more expensive than above, interpretation advanced, might be good to detect leak from site
SP	A. 1),2),5), B. 1),5) F. 6)	Measurements not primarily sensitive to leaks from dumpsites
IP	A. 1),2),3),5) B. 1),2),4),5) F. 1)[i,ii,iii,a]	More expensive than resistivity sensitive to clays and possibly certain types of chemicals, interpretation advanced
Seismic, Surface reflection/ refraction	A. 1),2),3),5) B. 1),2),3),4),5) C. 1),3) F. 5)	Will work in conductive materials, will detect saturated soil in unsaturated host soil, inexpensive, portable
Seismic, High Resolution (SONAR)	A. 1),2),3) B. 4),5) F. 5)	May be useful to sound conductive liquid impoundments

*See text for listing of Factors

(Continued)

TABLE 6. (Continued).

METHOD	FACTORS*	REMARKS
Borehole Techniques		
Resistivity Logging	A. 1),3),5) B. 1),2),3) C. 1) F. 1)[i,iii,a)],2),4)	Easy to use, inexpensive, can see out from borehole a meter
SP Borehole	A. 1),3),5) B. 1),2),3) C. 1) F. 6),4)	Easy to use, inexpensive
Resistivity Hole-to-Hole	A. 1),3),5) B. 1),2),3),4) C. 1) F. 1)[i,iii,a)],2),4)	May be useful to detect leachate under liner
HF Pulse, Single Hole	A. 1),3),5) B. 1),2),3),4) C. 1), F. 1)[i,iii,b)],4)	Can be used to look out up to tens of meters from a single borehole
Hole-to-Hole		Can look between boreboreholes
CW HF, Hole-to-Hole		As above, greater range, more difficult to interpret data
Seismic, Hole-to-Surface	A. 1),3),5) B. 1),2),3),4),5) C. 1),3) F. 5)	One hole needed, can work in conductive ground
Seismic, Hole-to-Hole	A. 1),3),5) B. 1),2),3),4) C. 1),3) F. 5)	Can work in conductive ground, can give bulk seismic properties of ground under site
Acoustic Emission	F. 7)	May be useful for detecting flow through liner especially in liquid impoundment sites

*See text for listing of Factors

TYPING GUIDE SHEET

5) Homogeneity of waste material
6) Core data

C. Hydrological

1) Depth to ground-water table
2) Flow direction of ground water
3) Permeability of soils in the area

D. Geochemical

1) Geochemistry of the area
2) Well data
3) Chemical properties of waste materials
   (propagation rate and attenuation of leachate in soil

E. Biological

1) Vegetation in area (any anomalous characteristics)

F. Geophysical

1) Electrical properties of: i soil
   ii waste at a) low frequencies
   iii leachate b) high frequencies
2) Resistivity measurements
3) Conductivity measurements
4) Borehole logs from area
5) Seismic wave propagation and attenuations
6) Self-potential effects
7) Acoustic emission measurements
8) IP effects

Leak Detection Systems in Existing Sites

As discussed earlier, leak detection at existing sites is complex and has special difficulties. The problem is severe enough to rule out leak detection, per se, at most existing sites. Thus the purpose of this study is to identify systems and techniques that might indicate a leachate contamination problem after it has left the site area but while it still resides in the unsaturated zone and has not yet penetrated the ground water.

In planning a leak detection program all available background information on the geology, geography and hydrology of a site should be studied carefully. These models showing stratigraphy, material type and possibly electrical and acoustic properties, if available, will aid in deciding what combination of geophysical techniques are likely to be the most practical.

The preliminary model of the site, and the source and the type of leachate, will probably indicate which available techniques are most likely to give useful information. The areas and types of field surveys will also be indicated. If little is known about the site or the electrical properties of the waste material and the soils around it, it is worthwhile to first carry out a relatively inexpensive electromagnetic survey to determine bulk electric properties. A mutual inductance or a very low frequency (VLF) wave tilt survey will permit a very rapid and inexpensive survey to be carried out and will result in a rough measure of apparent conductivity versus position. This survey will indicate whether or not a more costly high-frequency (HF) pulse survey should be carried out. If the overburden is very conductive (resistivity less than about 50 ohm meters) then the HF pulsed system is unlikely to penetrate more than a few meters. This may or may not be satisfactory. If the ground has a bulk resistivity greater than 50 ohm meters then the pulsed system will likely give a high resolution map of electrical variations to a depth of 10 or 20 meters. However, metal objects like drums will generally shield any reflectors below them.

A seismic survey will only be useful for detecting leaks if the ground water table is much deeper than the bottom of the liner. The seismic technique offers the opportunity for sounding in sites where the waste material, such as a brine, is very conductive and no electrical techniques will be effective. The high resolution seismic techniques like sonar offer an excellent potential opportunity to map and sound the clay liner in liquid sites. A contaminant site filled with inhomogeneous solid waste will cause the seismic waves to be seriously attenuated and scattered and thus will be difficult to interpret.

Resistivity techniques seem to offer good opportunities to look inexpensively for leachate plumes. A conductive overburden greatly reduces the effectiveness of the technique. The pole-dipole technique offers the potential to look for and monitor the growth of a leachate plume. In this technique the conductive material in the containment site is used as a current electrode while the other current electrode is far away from the site. The potential electrodes are then moved over and around the site; any anomalies measured are indications of a possible leak. Obviously, as in all the geophysical techniques, many measurements over time indicating a change will be more confidently interpreted as being associated with the movement of a leak.

The self potential (SP) technique may only be of use when a long-term monitoring program of a site is planned. Measured changes in self potential may be due to flow of a leachate or increased extent of the conductive leachate in the soil. The measurements are easy to carry out in the field but the number of variables that may give SP anomalies are large and thus the interpretation of that data is difficult. Most of the active techniques offer more information for each measurement. This is indicated in the matrix by the low ratings in both the "technical factors" and "sensitivity." All the other parameters get high ratings pulling up the "overall average" but because of the limited information obtained in the field, a large amount of data reduction will provide little additional information.

There are far too many variables for a complete hypothetical study to be carried out here. Thus we will limit our examples to two possible situations; one a liquid containment pond and the other a solid waste site that has leaking drums.

Hypothetical Liquid Site--

The liquid containment pond is about 100 m^2 and 5 m deep. It contains toxic and conductive liquid. The pond has an impermeable clay liner about 0.5 m thick over a course grained sandy, silty soil. The water table is usually about 8 to 10 m deep. No leachate has been detected at any of the observation wells.

The conductive liquid will probably mask any variations underlying the site if electrical methods are employed from the surface. The large surface area practically eliminates all the transillumination techniques used from borehole to borehole at the site periphery; however, various borehole methods might be useful for detecting anomalous areas below the site and approaching its outer limits. Since there should be good electrical contrast of the conductive leachate in the resistive sub-soil, borehole radar surveys might be useful. SP measurements might also indicate the presence of anomalous potentials, which in turn might indicate leachate in uncontained areas. Background surveys and comparative surveys over a year or so will help confirm if there is really an anomaly and if it is changing. If few boreholes exist then the best surface measurement might be the pole-dipole resistivity technique.

One current electrode is placed in the conductive liquid and the other current electrode placed away from the pond and probably down stream would be best. Then the two potential electrodes that are kept at a constant separation, which is greater than the depth of the pond and liner, are moved over a grid on the pond. If a leak does exist in the liner then a significant resistivity anomaly should be measured. The location of this anomaly is likely over a leak in the liner and further finer spaced surveys should be carried out.

Once the presence of a leak has been established acoustic emission sensors could be located near the questionable area, with a few placed away from the area to establish the ambient background noise level. The leaking fluid may generate a detectable sound source. The sound amplitude would increase as the sensor approaches the leak.

High-frequency electromagnetic techniques should be considered if the liquid is not too conductive (i.e., <0.02 mhos per meter). The antennas can be placed on the liquid surface or towed near the bottom of the pond. The high-frequency techniques offer the potential of obtaining a high-resolution short-range map of the liner. In a very conductive liquid the high-frequency electromagnetic techniques will not be practical.

Further experiments are necessary to determine what, if any, techniques exist or can be found to monitor leaks from existing lined sites. However, as has been emphasized, the use of composite geophysical surveys to monitor for changes or variations in several different soils and materials properties greatly enhance confidence in program results.

Solid Site--

The solid waste site is about 100 m^2 and 5 m deep. A larger or deeper site only makes using "state-of-the-art" geophysical techniques more difficult and therefore less likely to be successful. A liner, 0.5 m thick, of impermeable clay was put down over a course-grained base. The site contains 45 gallon drums of very toxic chemicals and backfill.

It is thought that a number of drums have corroded and are leaking. There is no accurate map indicating drum location. The objectives are 1) to locate the drums, 2) to determine which drums are leaking, and 3) to measure the extent of any leachate both inside and outside the liner. Magnetometer surveys are most sensitive to the drums and the technique is easy to use and least expensive of any of the methods discussed in the matrix. The technique is not useful for detecting wastes leaking from impoundment sites. Techniques such as DC resistivity, mutual induction, wave tilt, and pulse radar may also be used to detect metal drums but are difficult to use and more expensive.

The problem of estimating the extent of the leachate under the liner is extremely difficult until the leachate plume extends beyond the liner. The clay liner will, in most cases, not let the radar pulses penetrate. The DC resistivity and VLF wave tilt methods may be the only hope and the interpretation of the data will be very difficult.

Flow Chart for Existing Site--

A flow chart, outlining the general procedure to be followed to determine the presence of a leak at an existing site, and then to evaluate the leak is shown in Figure 6. This flow chart can be used as a basic tool in designing a leak detection program and can be altered to fit each individual site depending upon the following factors:

- the information known
- the specific problem
- the specific objectives
- available monies
- potential and actual impacts of a leak.

Thorough site evaluation and careful program planning will do much to assure that the full potential of any composite leak detection survey will be realized.

Leak Detection Systems in Planned Sites

The problem of leak detection systems for planned sites offers the potential for satisfactory solution within the 1 ft^2 (0.1 m^2) objective. However, at this point no such system exists so any discussion of the problem and its solutions must be regarded as conceptual. Unlike existing sites, at planned sites it will be possible to actually build leak detection systems into the disposal site, either in the liner material itself, or underlying the full areal extent of the

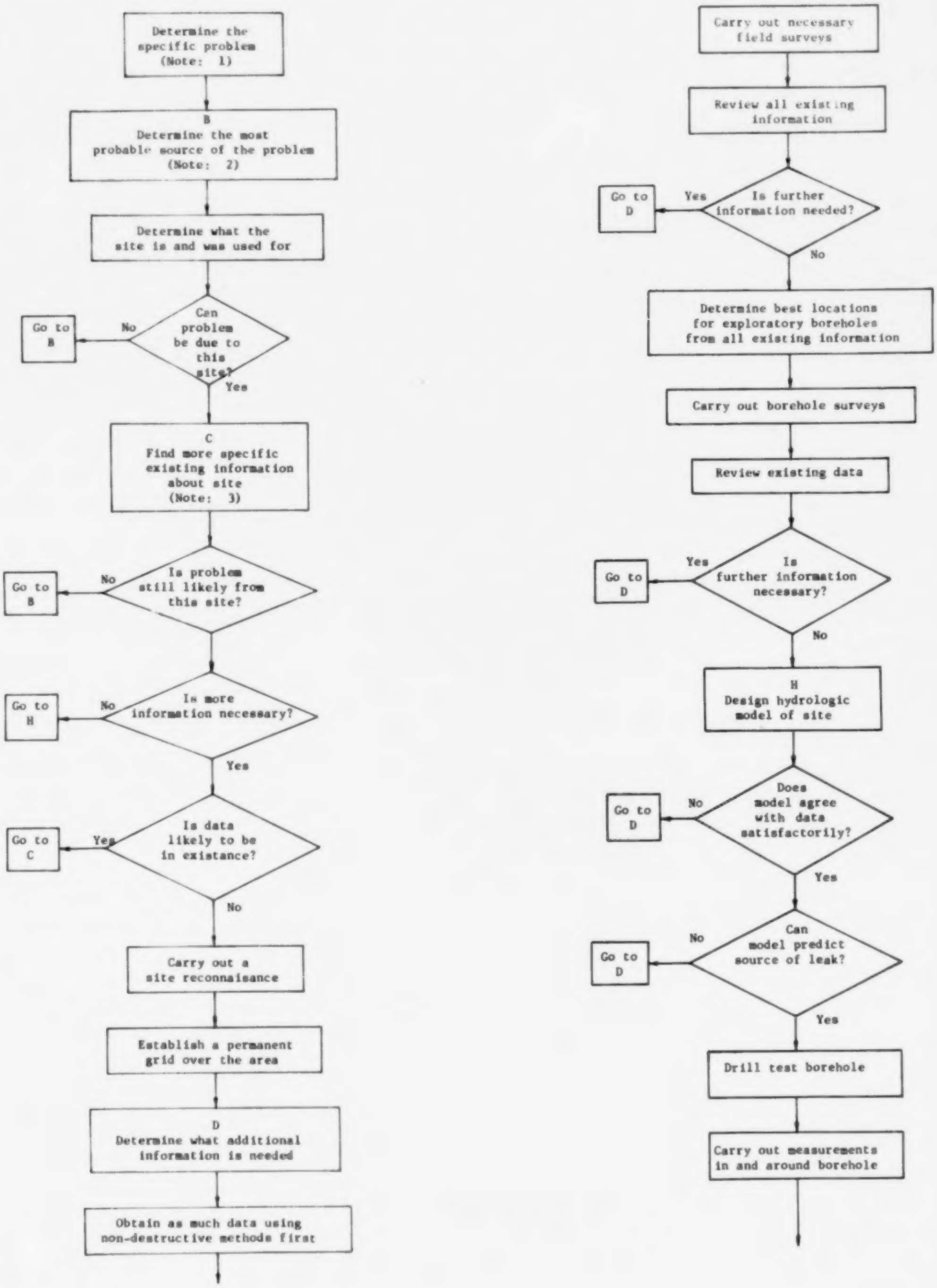
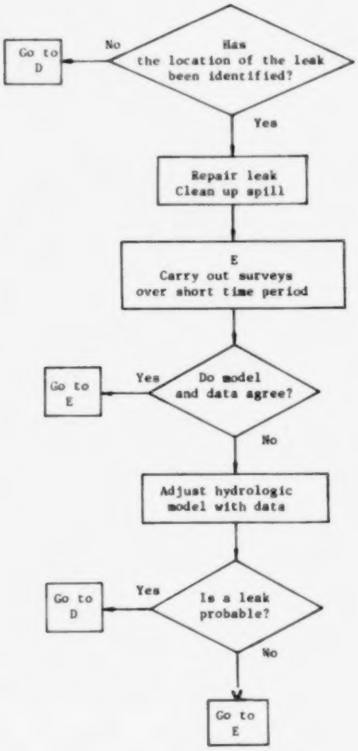

Determine the specific problem (Note: 1)
B
Determine the most probable source of the problem (Note: 2)
Determine what the site is and was used for
Can problem be due to this site?
No
Go to B
Yes
C
Find more specific existing information about site (Note: 3)
Is problem still likely from this site?
No
Go to B
Is more information necessary?
No
Go to H
Yes
Is data likely to be in existance?
Yes
Go to C
No
Carry out a site reconnaisance
Establish a permanent grid over the area
D
Determine what additional information is needed
Obtain as much data using non-destructive methods first
Carry out necessary field surveys
Review all existing information
Is further information needed?
Yes
Go to D
No
Determine best locations for exploratory boreholes from all existing information
Carry out borehole surveys
Review existing data
Is further information necessary?
Yes
Go to D
No
H
Design hydrologic model of site
Does model agree with data satisfactorily?
No
Go to D
Yes
Can model predict source of leak?
No
Go to D
Yes
Drill test borehole
Carry out measurements in and around borehole

Figure 6. Flow chart for existing site.


Go to D
No
Has the location of the leak been identified?
Yes
Repair leak
Clean up spill
E
Carry out surveys over short time period
Go to E
Yes
Do model and data agree?
No
Adjust hydrologic model with data
Go to D
Yes
Is a leak probable?
No
Go to E

Note 1 To determine the specific problem ask the following:

a) who or what is affected,
b) what are the effects,
c) what is causing the effects,
d) where is the problem occuring, and
e) when was the problem noticed?

Note 2 To determine the most probable source of the problem review the following:

a) topographic maps of area,
b) reports from public,
c) area building maps and plans,
d) aerial photographs of area,
e) geological maps of area, and
f) hydrological data of area.

Note 3 To find more specific existing information about the site review the following:

a) topographic maps of site,
b) time sequence aerial photographs,
c) archives for history of site,
d) all site building plans and maps,
e) existing geological maps of site
f) existing hydrologic maps of site,
g) existing geochemical data of site,
h) existing geophysical data of site
i) sample existing wells,
j) personal information from contractors and from persons associated with dumping.

Figure 6. (Continued).

liner. As in the case of existing sites, the leak detection program begins with careful review of site hydrogeology and electrical properties of the soils in the vicinity and beneath the proposed site. In addition, the potential hazards posed by the location of the site and the wastes being impounded, and the funds available for leak detection, must be evaluated, and a program selected accordingly. Essentially, the economics of leak detection systems for planned sites dictate a trade-off between precision and accuracy and cost effectiveness. The wisdom of such choices will be indicated by the potential severity of impacts and the resulting liabilities that might be incurred.

In planning a program for an existing site the techniques discussed below offer potential for success.

AE Grid--

The acoustic emission (AE) technique probably offers more potential for long-term use at planned sites than in existing ones. Flow of a liquid through a soil can generate sound. The greater the flow through the pores the greater the amplitude of the sound. It is conceivable that a leak from a containment area will generate sounds that can be detected. The technique has been proven useful in detecting leaks in earth dams. Work is still necessary to determine amplitude of sound generated at low flow rates expected from leaks at a disposal site. It is not clear if the acoustic emission from a leak will be detected in the presence of noise from the waste material itself and natural ground-water flow. Significant data analysis will be necessary to extract the desired noise from the background noise.

DC Grid--

The DC grid technique requires that a grid of wires be placed under the containment site before the waste is impounded. It is thought that the wires will corrode due to the leak material, thus breaking an electric current passing through the wire or wires whose position is known. Obviously, if the grid is very coarse then the leak may occur between the wires and not be detected. Any break in a wire for other reasons besides a leak will render that wire useless. There is also some difficulty in estimating the volume of leak that has occurred before the wire will corrode. As the grid spacing is made finer the cost increases rapidly and the technique is not practical. The equipment and measurement technique is quite simple but the information obtained is also very limited. (Figure 7)

TDR Grid--

The TDR grid technique also requires a grid of wires placed under the containment site, but the technique is sensitive to changes in electrical properties associated with a leak between pairs of parallel wires. A short pulse of high-frequency energy is propagated between the pair of wires and some energy is reflected whenever there is a change of electrical properties like moisture content. The maximum spacing between the wires at which pulses can propagate and the maximum propagation range of a pulse still needs to be determined. The wires can be insulated to prevent corrosion. If a wire breaks, it can still be used to give useful information and the location of the break can be determined. A great deal of experimentation is necessary to determine the usefulness of the technique but conceptually the TDR technique offers great potential. Wire separations of about 1 meter might be used to propagate a low-frequency pulse and monitor possible leaks between the wires.

To carry out the TDR measurements, access to the ends of the grid wires is necessary. A pulse source and receiver must be connected to a pair of grid wires and a response of reflections versus travel time is observed. Comparative measurements with time should be carried out. A break in the wire will be uniquely detected. Leachate flow in the cable should be easily detected also. The response will be similar to increased water content as from the ground water, but ground water should affect many wires in a similar way. TDR then can actually be used to see out beyond the wires themselves. It can also locate the position of a leak along a parallel wire without the need for a cross-grid as in the DC technique.

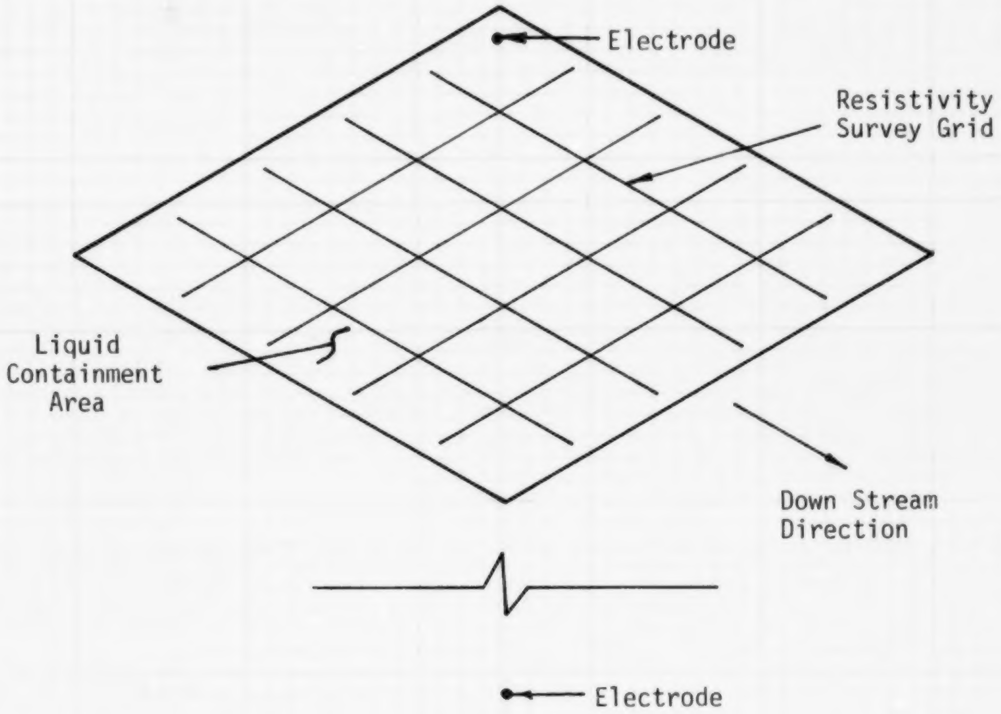


Figure 7. DC grid technique.

As in the case of leak detection systems at existing sites, it will be wise to utilize a composite geophysical monitoring system. Thus, for example, a system might be designed to emplace both AE sensors to evaluate liner integrity and a TDR grid to monitor for changes in soil conductivity, underneath the same liner system. This would have particular value when extremely hazardous wastes are impounded.

Optimum Site Configuration

The optimum design of a waste site when very hazardous liquid wastes are impounded is a long narrow trench or a series of parallel trenches as shown in Figure 8. Boreholes placed at distances of up to 30 meters apart can be drilled and should extend to about twice the depth of the trench. The boreholes should have plastic casing so that electromagnetic techniques can be used. DC resistivity measurements can be carried out through perforated plastic casing. If the boreholes are dry, a number of conducting strips should be placed on the outside of the casing so that DC resistivity and SP measurements can be made. Note that these holes can also be used for water quality sampling. Once the site is in use repeated geophysical measurements should be carried out a number

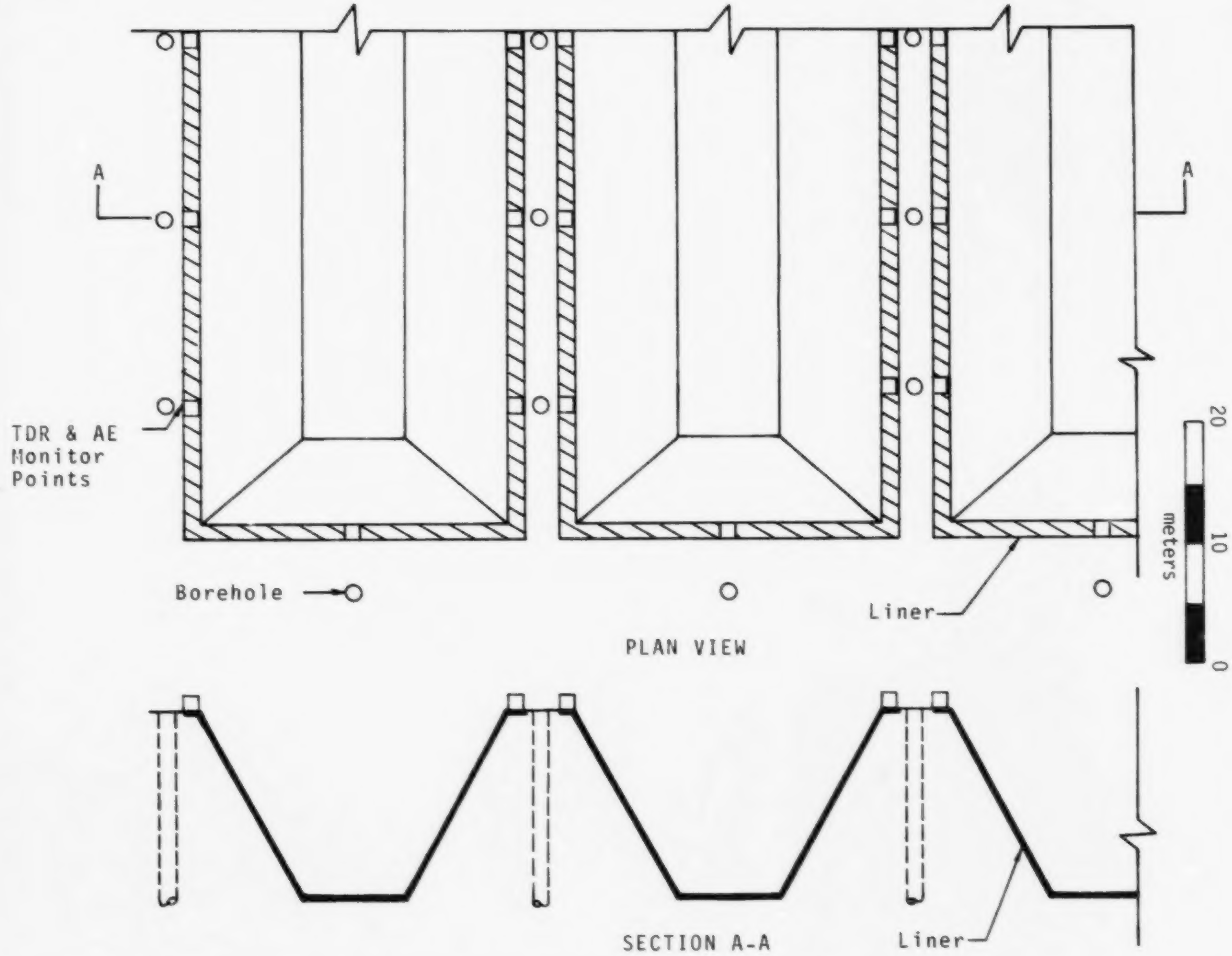
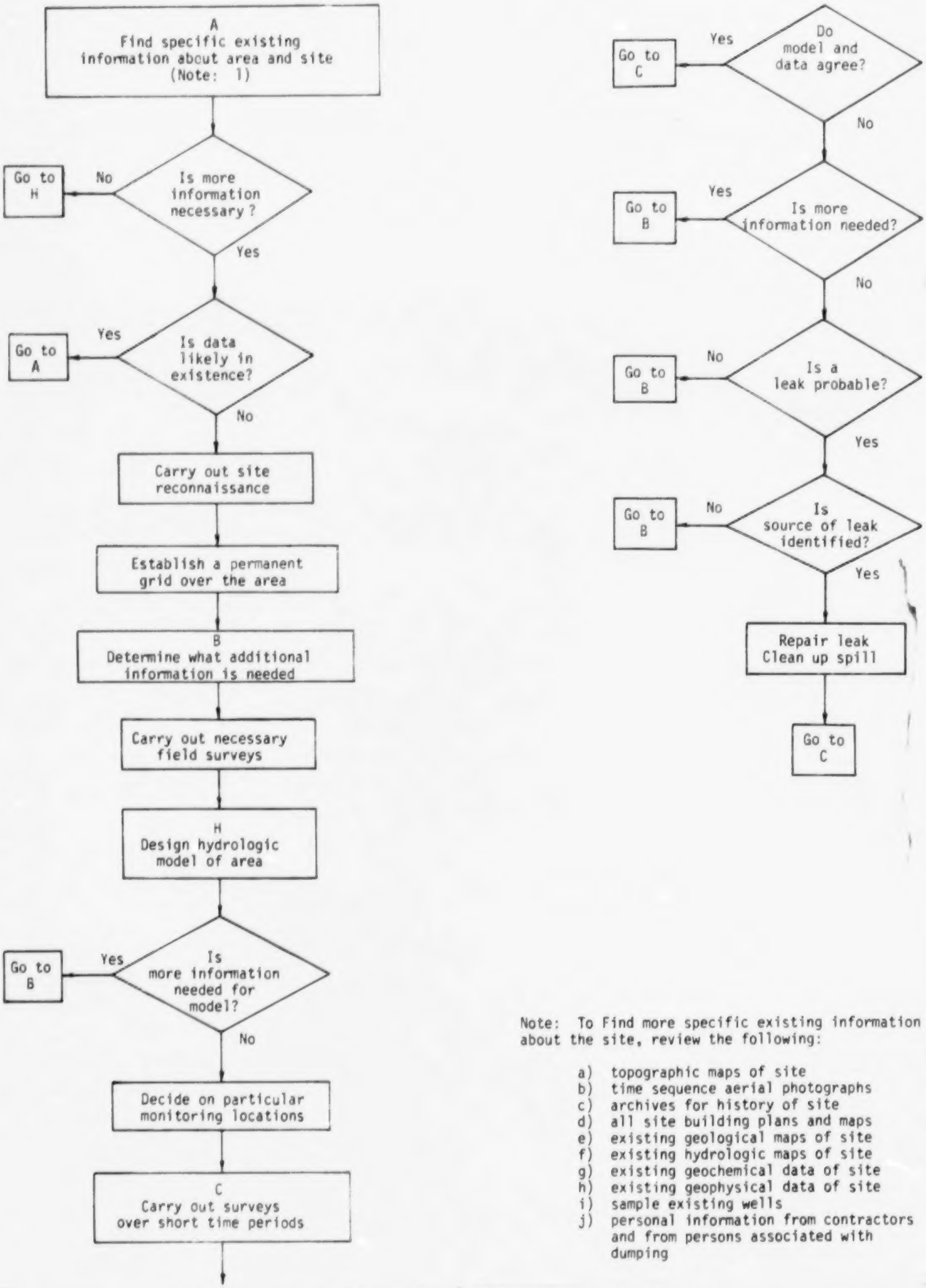

A
A
TDR & AE
Monitor
Points
Borehole
Liner
PLAN VIEW
20
10
0
meters
SECTION A-A
Liner

Figure 8. Proposed waste dump site design.

TYPING GUIDE SHEET


A
Find specific existing information about area and site (Note: 1)
Is more information necessary ?
No
Go to H
Yes
Is data likely in existence?
Yes
Go to A
No
Carry out site reconnaissance
Establish a permanent grid over the area
B
Determine what additional information is needed
Carry out necessary field surveys
H
Design hydrologic model of area
Is more information needed for model?
Yes
Go to B
No
Decide on particular monitoring locations
C
Carry out surveys over short time periods
Do model and data agree?
Yes
Go to C
No
Is more information needed?
Yes
Go to B
No
Is a leak probable?
No
Go to B
Yes
Is source of leak identified?
No
Go to B
Yes
Repair leak
Clean up spill
Go to C

Note: To Find more specific existing information about the site, review the following:

a) topographic maps of site
b) time sequence aerial photographs
c) archives for history of site
d) all site building plans and maps
e) existing geological maps of site
f) existing hydrologic maps of site
g) existing geochemical data of site
h) existing geophysical data of site
i) sample existing wells
j) personal information from contractors and from persons associated with dumping

Figure 9. Flow chart for planned site.

of times a year. Any unaccounted change in response over time must then be investigated further. The data should be obtained in a way that they can be put in a computer for rapid comparative analysis.

A planned liquid waste disposal site is likely to have the earliest occurrence of potentially serious leaks. These sites must be very well lined and monitored. The above design for a site offers the optimum physical arrangement for state-of-the-art monitoring equipment. Each site will have different limitation and thus some of the methods may be impractical. For example, if the ground is very conductive or if the boreholes are more than 30 m apart, then continuous wave/high-frequency (CW/HF) techniques. The drawback of the CW/HF method is that costly data reduction techniques are necessary. In any case, a composite of techniques is necessary to try and obtain as unique and precise a solution as possible.

The primary differences between a planned solid and liquid waste disposal site are the amount of material available to leak in the liquid site, and the fact that potentially a liquid dumpsite may leak as soon as the liquid enters the site. Liquids emplaced in drums will probably not leak in the first few years of emplacement. This only means that in the drum-contained liquid and in the solid wastes disposal sites, fewer monitoring measurements need to be taken in the first few years compared to the free liquid disposal site.

Flow Chart for Planned Site

A flow chart, outlining the general procedure to be followed to design a leak detection system for planned sites, is shown in Figure 9. As in the case of the flow chart described for existing sites, this flow chart can be altered to fit each individual site depending upon site information, program objectives, and the possible economic and environmental impacts should a leak occur. However, actual implementation of such a system at a planned site must await the results of on-going research in the field.

SECTION 6

SUMMARY

This review and assessment of candidate leak detection techniques for existing and planned lined waste disposal sites has attempted to summarize the state-of-the-art in leak detection technology. Ultimately, the purpose of any leak detection technique is to identify the point source of a hazardous contaminant plume in time to execute effective repairs and to minimize possible damage to the environment. Techniques that have actually been applied to leak detection as well as those that have conceptual applicability to the problem were identified and reviewed in the course of an extensive survey.

SUMMARY

The goal of the program was to identify and evaluate non-destructive monitoring techniques according to their ability to detect a leak in a waste impoundment liner within the accuracy of 1 ft^2 (0.1 m^2). The results of the literature survey necessitated a modification in this broad program goal. In existing sites, limitations upon any possible nondestructive leak detection techniques made it necessary to broaden the goal of 1 ft^2 (0.1 m^2) accuracy, to include any technique that might improve upon the limitations of conventional ground-water quality monitoring practices. Thus any technique that has the ability to detect the presence of leachate moving out from a site prior to actual contact with the ground water was identified for evaluation and assessment in a Multiple-Ranking Matrix exercise. The matrix attempted to rank these techniques according to their leak detection potential, and to identify certain candidates as likely targets for future research and development.

In planned sites the 1 ft^2 (0.1 m^2) goal was retained as an ideal to work toward. However, it is important to note that this goal must be modified in consideration of site specific economic, technical, and environmental factors. Approximately 28 candidate geophysical techniques were reviewed in the literature survey. Of these, 20 were identified as having potential as leak detection techniques and were assessed during the ranking exercise. It should be noted that these techniques, in order to qualify for the assessment exercise, were assumed to work. Techniques that clearly would not work were eliminated.

Results of the survey and the ranking matrix indicated that there currently exists no single technique that is applicable in all or even many situations, particularly in existing sites. Each geophysical technique has both theoretical and site specific limitations. This makes it essential to use these geophysical techniques in a composite mode that will maximize their total capabilities. In addition, direct sampling and ground-water quality monitoring may often be necessary to give further confirmation to the results of the geophysical surveys. Several techniques were identified as having application to planned sites, but currently no leak detection systems are being utilized in the field. This program was valuable in identifying potential systems and in beginning to define the goals and parameters necessary and feasible for implementation.

The information drawn from the literature survey and the ranking exercise were summarized, and hypothetical applications of the various techniques to certain specific leak detection problems in both existing and planned sites were presented. These hypothetical applications of the various techniques to certain specific leak detection problems in both existing and planned sites were presented. These hypothetical studies emphasize the need for a systematic approach in planning and conducting total site assessments which may ultimately lead to detection of the actual point source of a liner leak. In addition, such a systematic approach allows a reduction in the time and costs expended. Finally, recommendations for future research efforts can be made, based on the results of the above effort.

RECOMMENDATIONS

Further research is necessary to demonstrate the advantages and limitations of a number of the candidate methodologies in different impoundment configurations. These would include both solid and liquid sites in various soil types, and should include an array of techniques used in a composite mode. For existing sites, a number of techniques exist that may be useful for looking underneath the impoundment and within the unsaturated zone. These include:

- Resistivity soundings - often used to evaluate existing leachate plumes, but not often applied in the unsaturated zone.
- Conductivity techniques - can be done from the surface without actual contact with the ground; should include both wave tilt and mutual inductance techniques.
- HF pulsed techniques (ground probing radar) - also can be used from the surface; cannot see through clays but can see a clay boundary.
- Seismic techniques - can evaluate mechanical rather than electrical properties at sites.
- Acoustic emission techniques - can be used in a site to zero in upon an identified leak.

It would be useful to begin this work at sites where the geology and background data are known, and where the existence of a leak has been determined by conventional means.

Audio magnetotelluric and transient EM techniques were eliminated from further review at this time, but offer future potential in existing sites because they may be able to see below conductive overburdens.

In planned sites three possible gridwork techniques have been identified:

- TDR - can be used to evaluate the soil between wires in a transmission line for changes in electrical properties. Can uniquely locate the source.
- Acoustic emissions - can possibly evaluate mechanical properties of the liner itself, as well as identify the presence of seepage.
- DC resistivity - can detect corrosion or a break within a wire. Cannot uniquely locate it.

The optimum configuration of a gridwork will depend upon the following:

- Site dimensions
- Economics
- Liner materials and installation techniques
- Data acquisition and reduction.

These decisions will be highly site dependent, varying with the degree of risk and the nature of the waste being impounded. Finally, pole-dipole techniques, currently being investigated by SouthWest Research Institute offer great potential in existing and planned lined sites.

Although no single technique or group of techniques have been identified as a solution to the leak detection problem, the group of techniques reviewed and evaluated here can be applied systematically and synergistically to existing lined sites with the eventual hope of detecting leachate contamination prior to damage to the ground water. Certainly such techniques should be applied routinely in conjunction with water quality sampling at any site identified as a potential problem, due either to its proximity to an important aquifer or due to the hazardous nature of the wastes impounded there. In the case of planned sites, several possible solutions hold out promise for future development, for leak detection and for monitoring of liner integrity as well.

APPENDIX A

STATE-OF-THE-ART REVIEW

RESISTIVITY TECHNIQUES

Resistivity techniques measure the bulk electrical properties of the subsurface. Data can be obtained by spatially sampling at a fixed electrode separation over a line which gives a profile, or by using different electrode separations over the same point which gives a depth sounding.

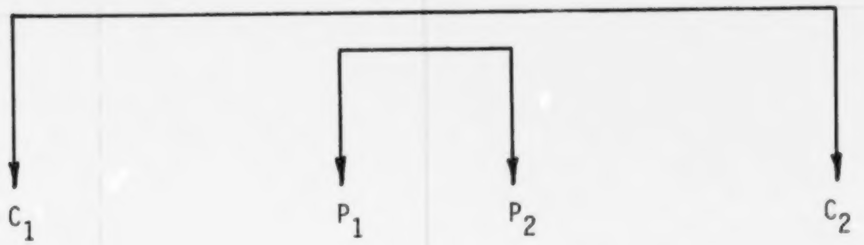
DC Resistivity

DC resistivity techniques have been used with varying degrees of success in locating contaminated ground water and leachate from waste impoundments. The degree of success is generally related to a variety of factors. The primary factors are the geology and hydrogeology of the area and the resistivity contrast between the leachate and the host material. Other factors can include cultural features such as buried pipes, metal fences, or large earth currents from local sources such as power lines and electric trains. A combination of several of these factors can make the resistivity method useless at some sites; yet at other sites, with simple and known geology and a highly conductive leachate, DC resistivity is one of the best and cheapest methods available. More specific examples are cited later, following the description of the techniques.

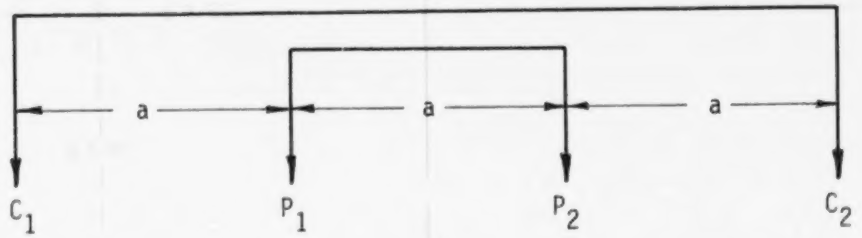
Almost all resistivity studies related to impoundment leaks have been concerned with monitoring leachate plumes after the impoundment has been breached. Therefore most resistivity surveys have taken place outside the site. Two electrode configurations have been dominant in these studies. They are the Wenner configuration and the Schlumberger configuration which are diagramed in Figure A-1. In both configurations currents enter the ground at the outer electrodes (C_1 and C_2) and the potential differences are measured at the inner electrodes (P_1 and P_2). In the Schlumberger array, the distance P_1P_2 is generally .1 to .2 times the separation C_1P_1 or C_2P_2. In the Wenner configuration the spacing between electrodes is equal, i.e., "a."

Resistivity surveys usually require two types of soundings. Electrical soundings that determine resistivity changes with depth, and electrical profiles that monitor lateral changes at a constant depth.

There are only minor procedural differences between the Schlumberger and the Wenner configuration. When electrical soundings are made with the Schlumberger array, the current electrodes remain fixed in place while the potential electrodes are moved. This is slightly more time efficient since only two electrodes are moved as opposed to four electrodes in the Wenner con-



Schlumberger



Wenner

Figure A-1 Common electrode configurations - DC resistivity.

figuration. In addition, the Schlumberger array used for soundings is less affected by surface inhomogeneity because the potential electrodes are not moved. In most cases, the choice of configurations is determined by the available equipment and the skill of the operator.

The use of resistivity methods to detect ground water or monitor contaminated ground water is almost as old as the method itself. Swartz [10] (1937, 1939) used it for detecting saltwater intrusion in Hawaii. Much more recently, it has been used to monitor leachate from impoundments and sewage treatment plants (Cartwright and McComas [11], Stollar and Roux [12], Berk and Yare [13], Fink and Aulenbach [14], Klefstad et al. [15], Hackbarth [16], Rogers and Kean [17], Kean and Rogers [18], Reed et al. [19] Greenhause and Harris [20]. The general concensus of these articles is that resistivity techniques can be very useful in detecting contaminated ground water. The constraints on obtaining good results are:

1. The geology of the site should be well known, and preferably simple. Complex stratigraphy make the results ambiguous (Klefstad et al. [21]).

2. The area for the survey should be large enough to allow the layout of the long electrical lines, uninhibited by fences, roads, and buried pipes. Such cultural objects will definitely limit the extent of the survey and the results. (See Fink and Aulenbach, 1974, as an example of such problems.)

3. The conductivity of the leachate should be high enough to give a reasonable contrast with the natural ground water. A ratio of 2:1 is sufficient, but interpretation is much easier with the higher contrasts.

4. Field operations and interpretation of the results are easier for shallow studies than deeper ones. This is primarily a problem of logistics, because the electrode spacings must be greater for deeper studies.

The following example demonstrates the usefulness of resistivity in detecting leachate from an active waste impoundment. These results are from an unpublished study by Kean, 1981. The site is located in an area of igneous bedrock which is overlain by 6 - 9 meters of glacial outwash sand. The geology near the site was determined from borings made before the impoundment was developed. The impoundment is used for the disposal of paper mill waste products. Figure A-2 shows the results of soundings using the Wenner array made at two locations in the downflow direction from the impoundment. Sounding 1 was made approximately 91 meters to the south of the site. The subsurface geology was identical at both sounding locations. Sounding 1 shows a slight dip in apparent resistivity at an a-spacing of 9 meters, indicating the water table is just above the bedrock. Sounding 2 shows a very large decrease in apparent resistivity at a potential electrode spacing of 9 meters which indicates a highly conductive leachate (approximately 2000 mhos) determined from well samples. Based on these soundings, a 9 meter Wenner profile was made in a north-south direction perpendicular to the ground water flow direction (Figure A-3). Figure A-4 shows that profile and shows the extent of the leachate plume.

Until quite recently, interpretation of electrical soundings had been quite tedious and in many instances ambiguous. However, with the development of computer techniques, interpretation can now be made even with programmable hand calculators (Koefoed [22], Davis [23]). If one combines laboratory studies of the conductivities of subsurface samples with computer modeling, it is possible to determine changes in the flow and conductivity of leachate at a waste impoundment over time (Rogers and Kean, 1980 [24]; Kean and Rogers, 1981 [25]).

Resistivity methods are quite inexpensive. A three-person team could make a complete survey of an average site (of about 10 acres) in three to four days. Initial interpretation could be done in two days by one person. For existing impoundments with few monitoring wells, resistivity is certainly one of the cheapest and fastest monitoring techniques. For proposed waste impound-

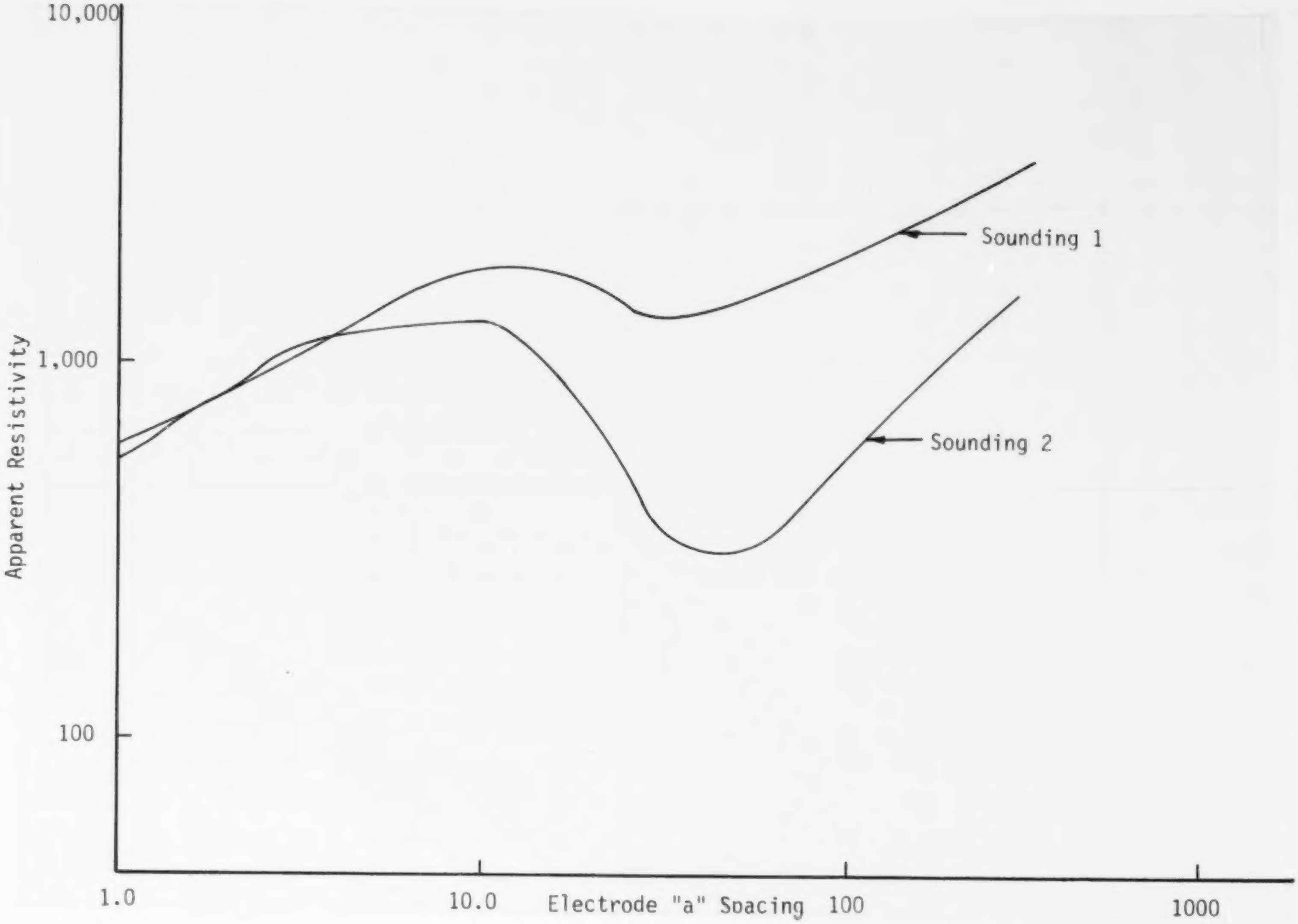


Figure A-2 Results of resistivity soundings made at two locations downflow from site. (Kean, 1981)

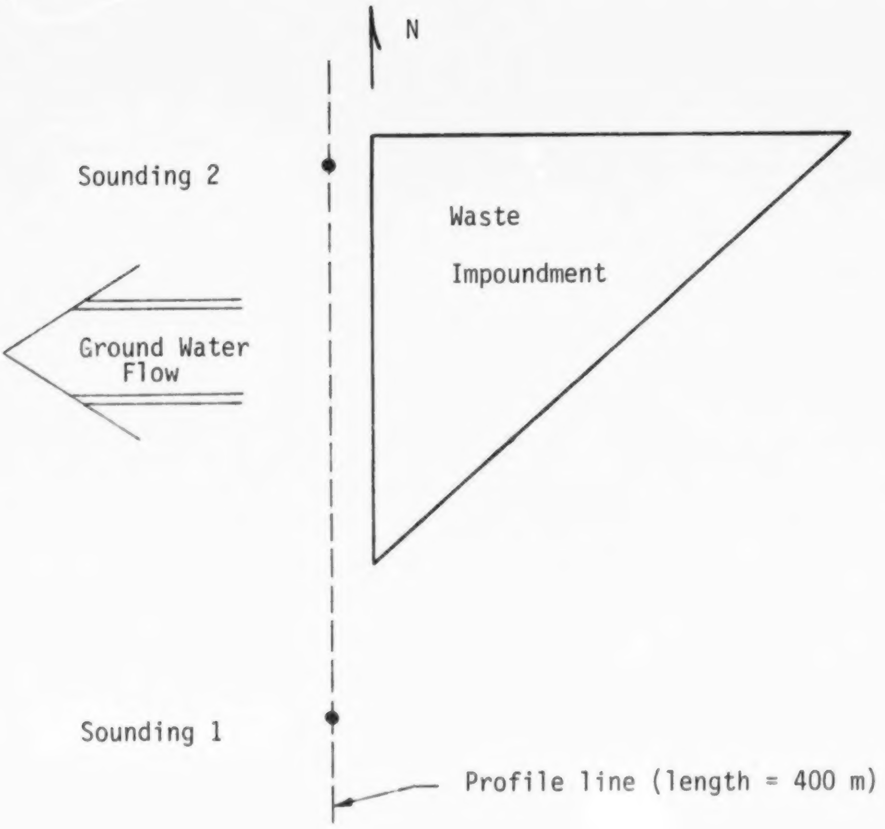

N
Sounding 2
Waste
Impoundment
Ground Water
Flow
Sounding 1
Profile line (length = 400 m)

Figure A-3. Map of waste impoundment.
(Kean, 1981)

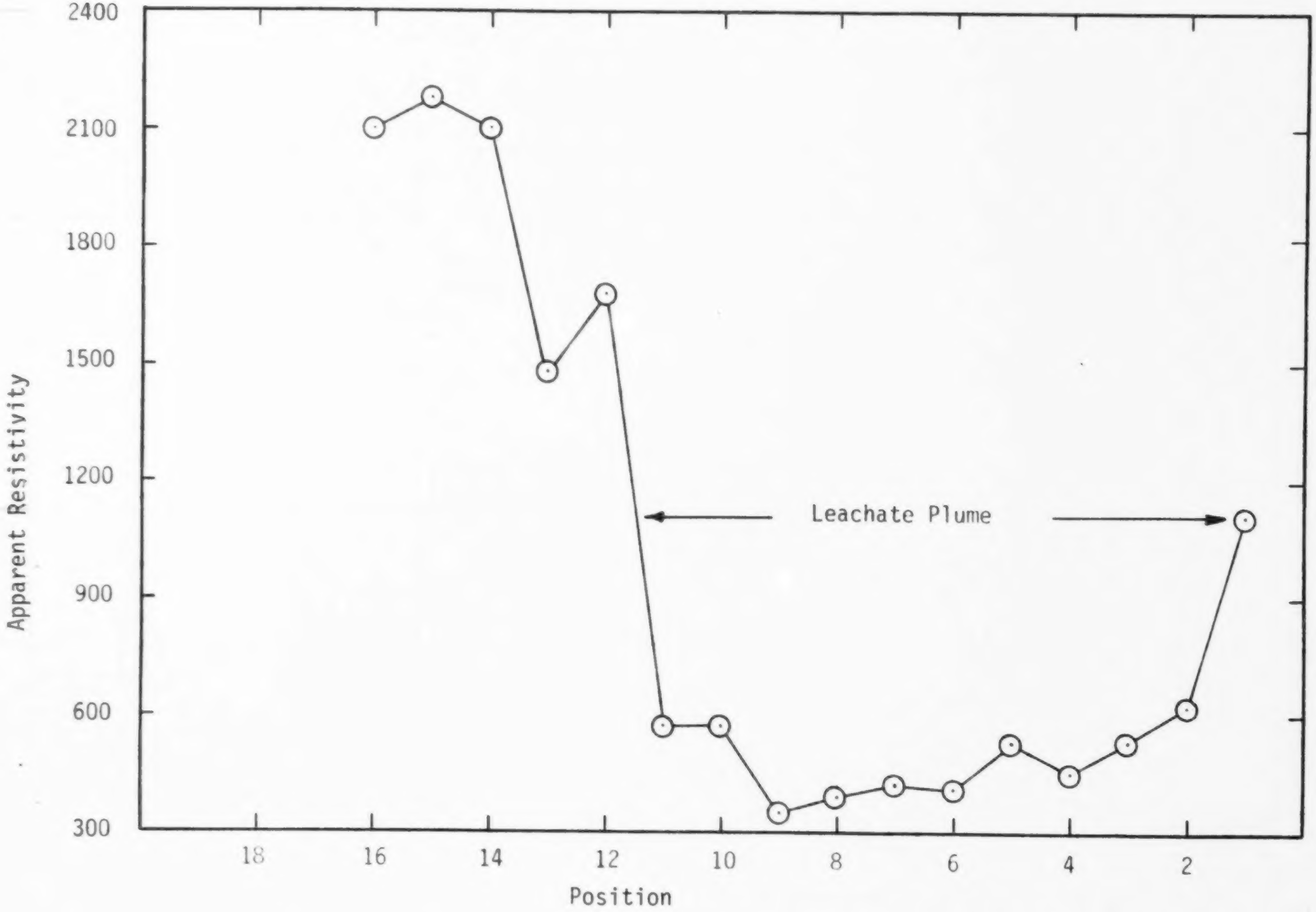


Figure A-4 Resistivity profile showing extent of leachate plume. (Kean, 1981)

TYPING GUIDE SHEET

ments, it would be well advised to have a resistivity survey of the area as part of background information. The Schlumberger and Wenner configurations, however, are not particularly useful in pinpointing the location of a leak in either a lined or unlined impoundment. In addition, the contamination must move outside the limits of the fill area before it can be detected because of the shielding effect of the waste site itself.

Pole-Dipole Configuration

The pole-dipole configuration will probably be the best resistivity technique for locating a leak in a sheet lined impoundment; it may also be effective in clay lined sites. This technique is undergoing investigation at the Southwest Research Institute under EPA contract No. 68-03-3033. This concept is well known in electrical resistivity surveys but not reported in the literature in reference to liner leak detection. The expected field configuration is given in Figure A-5. Current electrode C_2 is placed outside the impoundment site a great distance from C_1, such that it can be considered to be at infinity. A distance of 50 times "b" should be sufficient, where "b" is the distance between the two potential electrodes P_1 and P_2.

There are two ways in which the leak point could be detected, both of which assume that the liner material is highly resistive.

The first technique simply monitors the current flow between the two electrodes C_1 and C_2. Assuming a small leak in the liner, the currents will flow under the impoundment and enter it at the leak point. Electrode C_2 is kept stationary, while electrode C_1 is moved about inside the waste site. A minimum in the resistance of the current will occur when the search electrode C_1 is directly over the leak point, because the current path will be a minimum.

In the second technique, which employs the true pole-dipole configuration, the current electrodes are kept stationary, one inside and one outside, and the potential electrodes are moved. Distortions of the equal potential lines will indicate the location of the leak (Figure A-6).

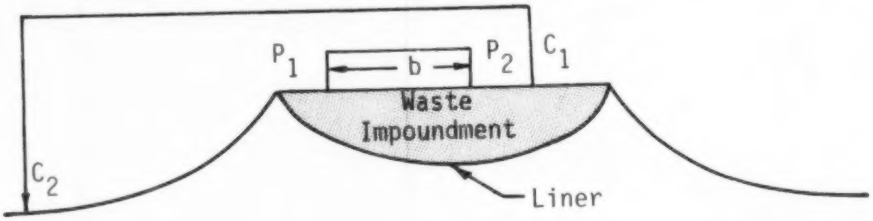


Figure A-5 Pole-dipole configuration.

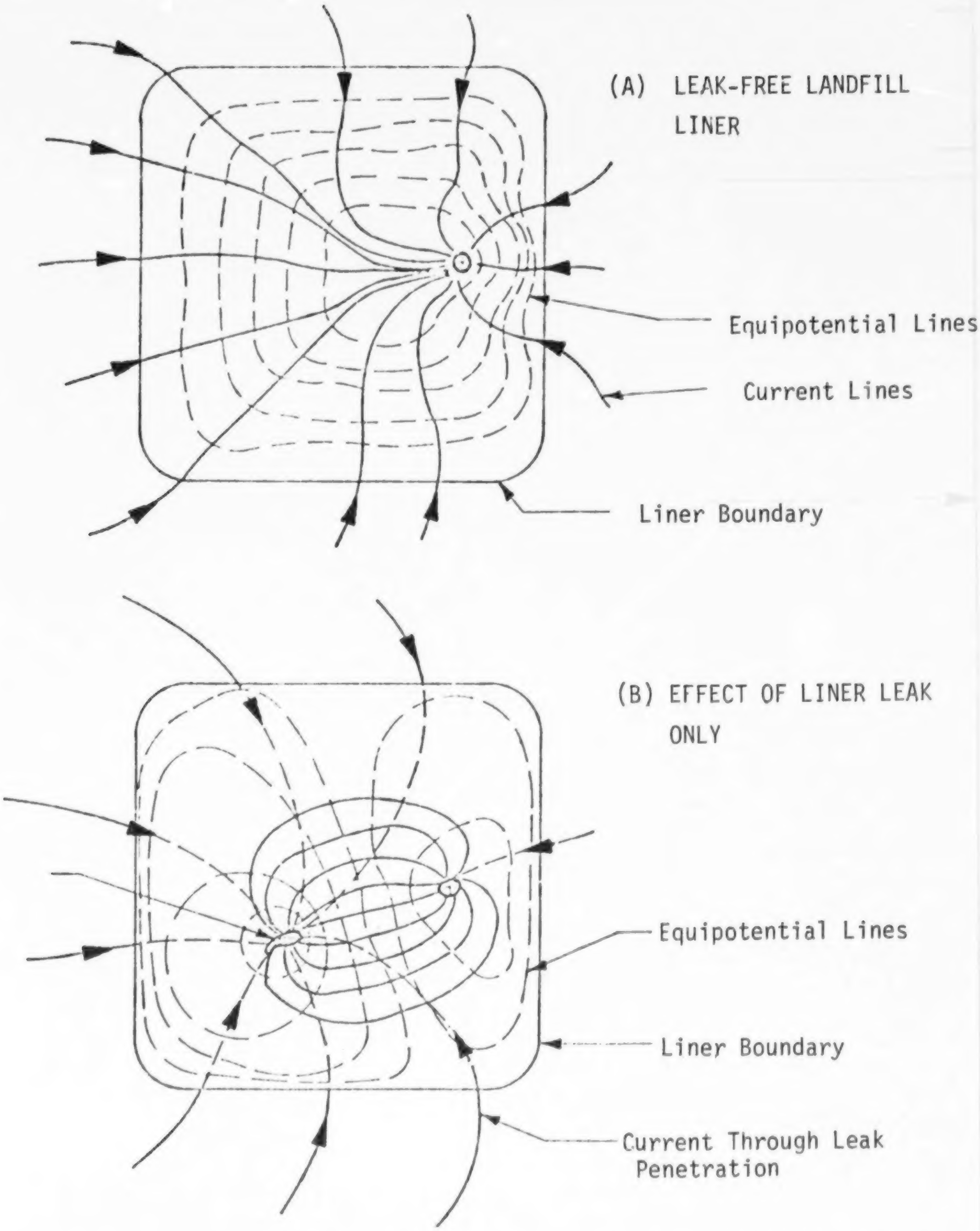

(A) LEAK-FREE LANDFILL LINER
Equipotential Lines
Current Lines
Liner Boundary
(B) EFFECT OF LINER LEAK ONLY
Equipotential Lines
Liner Boundary
Current Through Leak Penetration

Figure A-6. Equipotential lines on the surface of a landfill with current electrodes located on the landfill surface and outside the landfill. (Southwest Research Institute)

Both techniques appear to be effective at locating the leak to within 1 or 2 meters, depending on the equipment sensitivity and the depth of the impoundment. This sensitivity could be seriously reduced if a highly conductive leachate settled to the bottom of the site to the liner. This leachate could act as a conducting plate, which would then distribute the current flow uniformly over a large area of the site. However, this should be a site specific problem.

As proposed, this technique is technologically more complex than the other resistivity methods already discussed. Greater amounts of equipment are needed in the field, and data interpretation is more complicated. These considerations make this technique more expensive, but it may be a very effective technique for membrane-lined sites.

Induced Polarization (IP) or Complex Resistivity

Another technique which is compatible with resistivity studies is induced polarization (IP) or complex resistivity. Induced polarization has been used extensively by the mineral industry for locating disseminated sulfide deposits. Recent advances by the Kenneth Zonge Engineering Co. of Tucson, Arizona, indicate that it may be useful in studying contaminated ground water (personal communication with Richard Tinlin).

Induced polarization or the overvoltage effect is observed when the current in any of the standard four electrode DC resistivity spreads is interrupted. The voltage across the potential electrodes generally does not drop to zero immediately, but rather decays slowly after an initial drop from the steady state value. When the voltage change is measured as a function of time, the method is known as time domain IP. The buildup time of the voltage is also finite. Thus the apparent resistivity is a complex impedance; that is, the current and the voltage are not in phase. The IP effect can also be measured as a function of frequency. It is observed that the IP effect decreases with increasing frequency.

The IP effect is attributed to several sources. The greatest effect is due to electrode polarization at the boundaries of metallic conductors, such as disseminated sulfides. The next most dominant effect is the membrane polarization, which results from the movement of ions through the ore spaces of the subsurface material when subjected to an applied current. The membrane polarization will be a function of the size of the ions, the size of the pores, the concentration of the ions and the type of material being studied. For example, membrane polarization is more pronounced in the presence of clay minerals, because of the small pore size and the large number of ions attached to the clay particles.

Until quite recently, it was difficult to distinguish different types of materials using IP, other than distinguishing good conductors, such as sulfides or graphite, from nonconducting bedrock, such as granite or sandstone. Kenneth Zonge Engineering has made improvements in the interpretation technique which enables them to differentiate the less conductive materials from one another [26]. Their measurements consist of monitoring the phase difference between the applied current and the measured voltage at several different frequencies.

This technique is directly compatible with standard resistivity methods, because the same electrode spreads can be used, and DC resistivity measurements can usually be made with IP equipment. IP equipment is more expensive and more cumbersome in the field. However, one may be able to monitor subtle differences in subsurface materials that DC resistivity cannot. For example, DC resistivity measurements cannot distinguish a sand layer with a moderately conductive pore fluid from a clay lens, but it may be possible that the IP method can. Induced polarization or complex resistivity certainly warrants further study. Conceivably the IP method might be useful for determining the continuity of the clay liner at waste sites. It is conceivable that certain chemical wastes might have significant IP effects that can be mapped.

Borehole Resistivity Techniques

Borehole resistivity methods have not had extensive use in monitoring waste impoundment sites. There are several possible techniques that could be useful in detecting leachate once it has passed out of the impoundment. In addition, borehole resistivity information could be very useful as background data when a site is constructed.

The well-logging industry has already developed several borehole resistivity methods and the interpretation techniques to go with it. These are a variety of electrode spreads attached to a sonde which is placed down an uncased well or borehole. The electrode configurations are similar to either a Wenner or a pole-dipole configuration. The potential electrode spacing is usually either 40.6 or 81.3 cm (16 or 32 inches). The primary uses of borehole resistivity are to determine lithology, porosity, and conductivity of pore fluids, all of which are useful in stratigraphic correlation between boreholes and in ground water evaluation. This also has direct application in designing impoundment sites and monitoring them. However, to use these standard well-logging tools an uncased well must be used. Generally, monitoring wells near impoundments are cased with either steel or PVC pipe, both of which eliminate the standard tools for monitoring work after the site is developed.

Variations on this method can be devised. One possibility is to place electrodes with connecting lead wires on the outside of PVC pipe before it is placed in the borehole. Electrodes spaced at 30 to 91 cm intervals would provide a fairly detailed monitoring system for changes in water quality with depth. One can measure potential differences between pairs of electrodes or use the electrodes in a standard Wenner, pole-dipole, or dipole-dipole configuration. Conceptually, this technique has a limited range, that is, the contamination must approach within 1 or 2 meters of the well before it can be detected. In addition, corrosion of the electrodes will produce erroneous results with time.

If a series of wells with electrodes were placed around a site, then resistivity measurements could be made between wells. Potential differences can be measured directly between adjacent wells, and any changes with time will be related to changes in the conductivity of the pore fluid in either the saturated or unsaturated zone. One could also use the borehole electrodes as current sources and measure potential differences on the surface.

The techniques are obviously costly if one is installing wells just for resistivity monitoring. However, in the development of a new site, the additional cost would be minimal and the wells would have other uses.

Self Potential (SP) or Streaming Potential

If the resistivity techniques described above can be regarded as active techniques, then streaming potential, or self-potential, (SP) can be regarded as a passive resistivity technique.

The SP method is based upon measuring the natural potential differences that generally exist between any two points on the ground. This potential occurs due to electrochemical actions in the ground. Normally the potentials range around a few tens of millivolts in the ground and may increase to hundreds of millivolts over sulphide and graphite ore bodies.

Large potentials also occur over clays, marls, and other sediments. These large potentials are due to ionic layering, electrofiltration, pH differences, and electro-osmosis. For example, water flowing through sand on a sea beach sets up electrical potentials due to electrofiltration.

Field measurements typically are taken between a fixed reference electrode placed well outside the site and a measurement electrode is put in the ground at different points within the site. This produces a map of SP versus position in the site.

The SP technique may be a useful technique for indicating flow of leachate material and possibly for indicating problem areas in the clay liner. The technique is very dependent on soil type and waste type. Comparative surveys over long periods of time will be necessary.

Carrying out SP measurements in boreholes is likely to increase coupling to the subsurface, operate nearer to the source of seepage or flow, and possibly avoid the masking or shielding effects of the waste site itself.

The literature review indicated several examples of SP phenomena used to detect seepage from dams and reservoirs and earth dams. Haines [27], in Australia, reports similar results in tracing the flow of water from Brisbane reservoir (see Figures A-7 and A-8). Spontaneous potential profiles were obtained over the same line in a reservoir at different times of the year. The water level on Oct. 15, 1977, was 5 meters deep, whereas it was almost zero on Feb. 12, 1978. The hachured zones around 80 meters and 140 meters along the line are ascribed to leakage zones caused by increased flow and thus more negative SP's. These zones correlate with the observed positions of leakage on the downstream face of the nearby dam. In the United States the technique is being actively applied by the Corps of Engineers at Waterways Experiment Station, Vicksburg, Miss., to detect the flow of water from dams and reservoirs (personal communication with James Warriner and Stafford Cooper of the Corps of Engineers). It is also currently undergoing laboratory research by the Corps of Engineers, in an attempt to better understand the mechanism itself. Greenhouse, et al., attempted to trace a leachate plume at Bose Bordon waste impoundment using SP techniques but were unsuccessful [28].

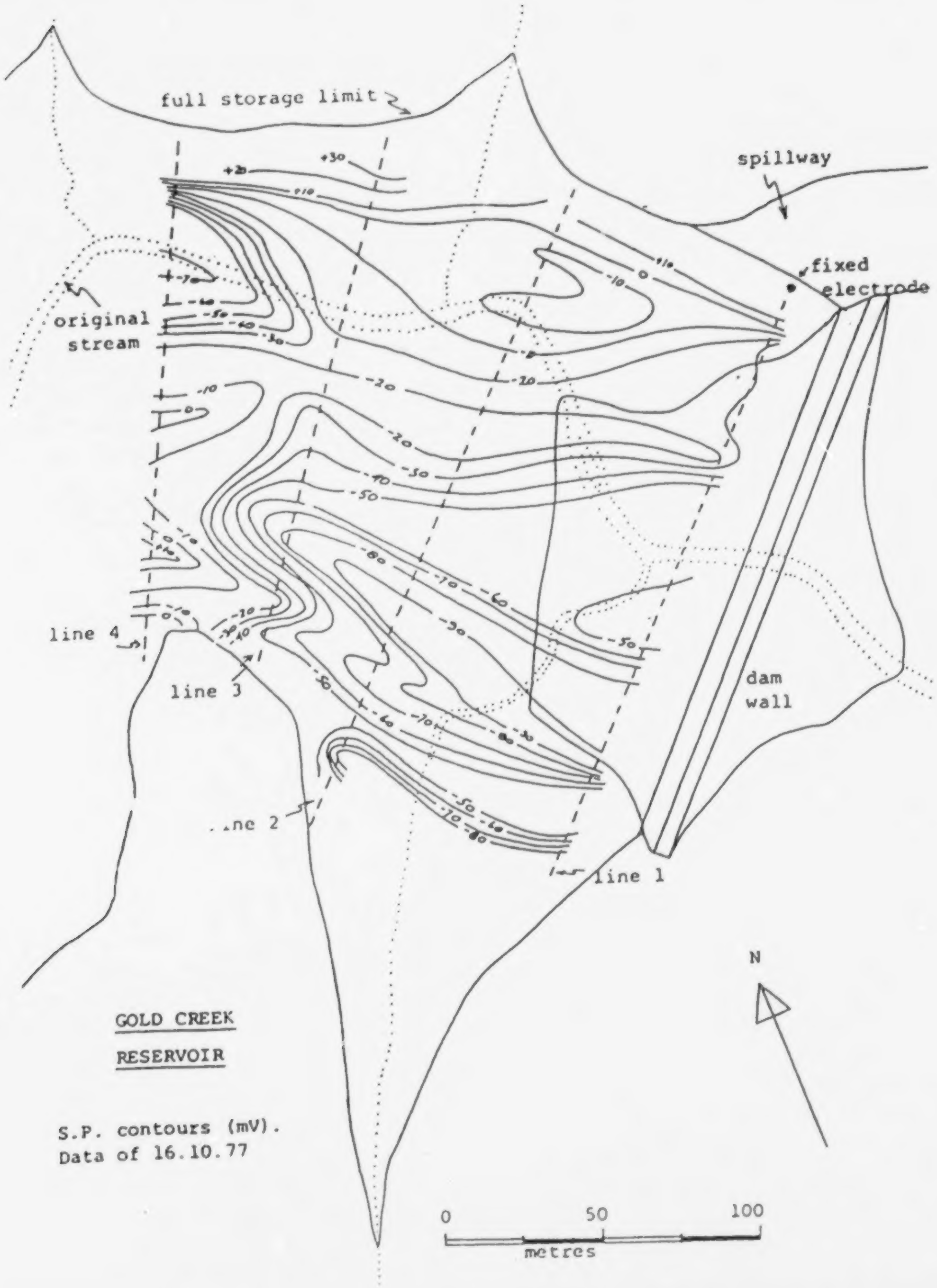

full storage limit
spillway
fixed electrode
original stream
line 4
line 3
line 2
line 1
dam wall
N
GOLD CREEK
RESERVOIR
S.P. contours (mV).
Data of 16.10.77
0
50
100
metres
+20
+30
+10
0
-10
-20
-30
-40
-50
-60
-70
-80

Figure A-7. SP Measurements at Gold Creek Reservoir. (Haines, 1978)

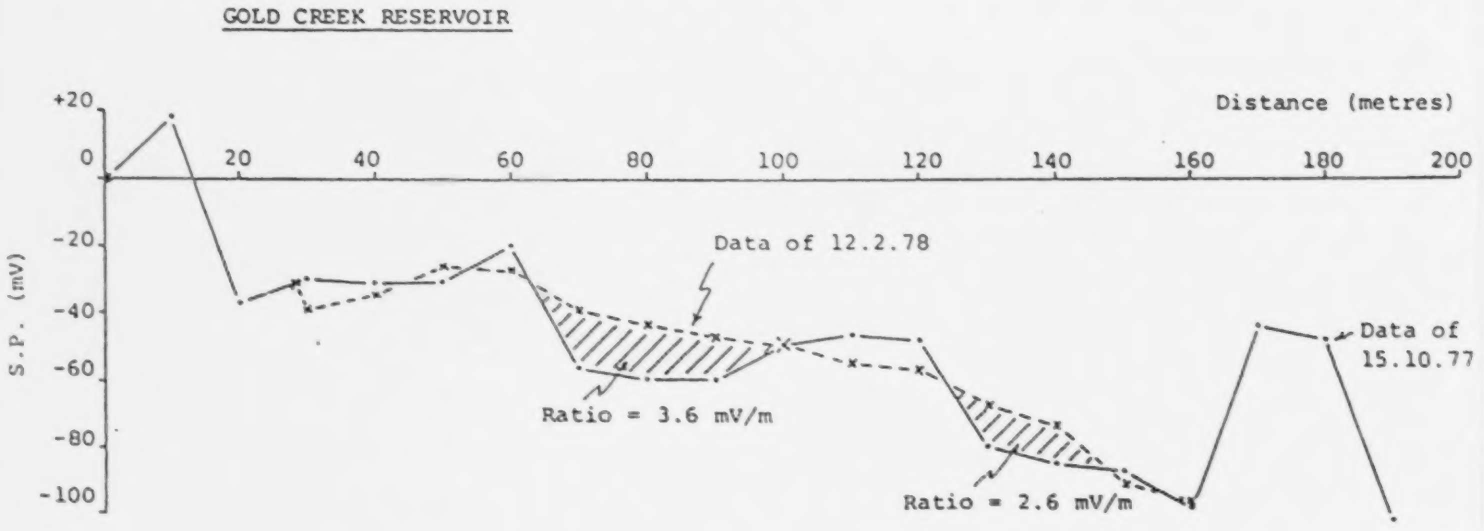


Figure A-8. SP measurements obtained at different times of the year at Gold Creek Reservoir. (Haines, 1978)

DC Resistance Gridwork

It may be possible to employ resistivity techniques in a permanent monitoring scheme by laying a grid of wires directly beneath a lined impoundment site or even by emplacing such a grid within the actual liner fabric or membrane [29]. The resistance of any single wire within the grid of wires could then be measured. If a break or significant corrosion were to occur along any wire, a change in resistance would give indication of a problem. If a cross wire in the grid were to change as well, then a problem would be likely to exist where the wires cross, to a precision of a grid square dimension. The practicality of this conceptual technique will depend upon several factors. Chief among these is the durability of the wires themselves, for it is impractical to emplace a monitoring system with a life expectancy significantly lower than that of the liner itself. Additionally, once failure of a wire has occurred, either from a leak incident or from natural degradation, it would be impossible to repair that wire, and the wire would no longer be usable for resistance measurements. A second consideration is cost, since the number of wires and the monitoring hook-up that may be necessary to obtain a reasonable coverage could be significant.

The advantages of this technique are several: It could be placed directly beneath a site. A monitoring schedule could be selected relative to site needs. Thus monitoring could be continuous in an extremely hazardous site, and less frequent in less hazardous sites. Once installed, both data acquisition and data reduction would be relatively simple.

ELECTROMAGNETIC TECHNIQUES (EM)

Electromagnetic techniques, like the resistivity techniques, produce a measurement of bulk electrical conductivity of the subsurface. However, unlike resistivity measurements, no electrode contact is necessary with the soil. Since a change in soil electrical conductivity can occur as a result of changes in soil moisture content, pore spaces, or soil or rock types, electromagnetic techniques can be effective in mapping changes in the natural geohydrologic features of a site, as well as mapping subsurface contamination from impoundment sites, lined or unlined. However, high conductivity layers near the surface will mask the conductivity variations at greater depths. Like the resistivity techniques, the EM techniques have a record of successful application as a leachate plume-detection technique at existing waste sites, and as a site assessment technique as well.

Mutual Inductance Technique

Mutual inductance techniques which measure the change of electrical coupling between two loops of wire appear to be the most commonly applied EM technique. Generally the equipment operates at frequencies in the kilohertz and tens of kilohertz range. A conductive body in the field of one coil generates a secondary current, which in turn couples to the receiver coil. The change in current at the receiver gives a measure of the conductance of the body. Generally, lower frequency and greater coil separation increase the depth of the interaction. The coil orientation with respect to each other and the ground alters the depth of penetration.

Field surveys are carried out by running the equipment on a grid with the coils at different separations or orientations to obtain a measure of the apparent conductivity over different depths. In the field it usually only requires minutes to obtain each measurement and a map of apparent conductivity versus position and depth may be interpreted rapidly.

According to Benson [30] the continuous coverage provided by EM methods from depths of less than a meter to 15 meters provides some significant benefits over the resistivity techniques. These include excellent spatial resolution and continuous coverage; in addition, the technique is relatively rapid and very cost effective. Raw field data can often be directly interpreted for first approximation results. Multiple parallel passes enable the technique to approach continuous three-dimensional spatial coverage.

The technique, like most geophysical techniques, is very site sensitive and EM performance can be degraded by cultural features; thus repeated measurements over long periods of time are necessary to observe any changes of conductivity surveys to detect leachate plumes has been reported in the literature. In 1980, Kolmer reported the use of EM techniques in a composite geophysical site assessment to detect and evaluate a leachate plume emmanating from Li Pari waste impoundment in New Jersey in 1980 [31]. Benson and Glaccum have used EM techniques to successfully evaluate polychlorinated biphenyl spills, to assess the diffusion of effluents as they proceed down gradient, and to evaluate salt/fresh water interfaces [32]. They also report its use to located buried drums [33] under several feet of soil. Greenhouse and Harris also report the use of EM conductivity surveys to evaluate leachate flow at the abandoned Bose-Borden waste impoundment in Ontario, overlying a sandy aquifer [34].

Two case histories, reported by Glaccum, Benson and Noel [35] are summarized here. A leachate plume, associated with a large waste impoundment site situated within an unconfined surface aquifer, had been monitored by more than 15 observation wells and well clusters for a period of 10 years. Major well clusters were placed southeast of the site in the direction of regional water flow. However, analysis of the well data was contradictory, since the plume to the southeast was poorly defined and high concentrations of leachate were also found in wells believed to be up gradient from the site. Electromagnetic techniques, in coordination with resistivity soundings were employed, requiring three weeks to cover the entire site. Field data included more than 8 line kilometers of continuous EM profiles as well as 75 deep EM and resistivity stations. The maximum extent of the leachate plume was revealed in the 30 meter results (Figure A-9). A broad plume was clearly present to the northwest, its size being much greater than that suggested by monitor well data. A strong narrow plume also exited to the south-southeast, somewhat south of regional ground water flow. None of the primary well clusters were found to lie on this main plume axis.

A shallow 6-meter, EM conductivity plot revealed that very high conductivities occurred in the areas around two farm ponds. It was found that the farm operators were pumping large volumes of water from 15-30 meter depths, creating a potentiometric low in the area northwest of the waste impoundment, permitting ground water flow in a direction opposite the regional gradient.

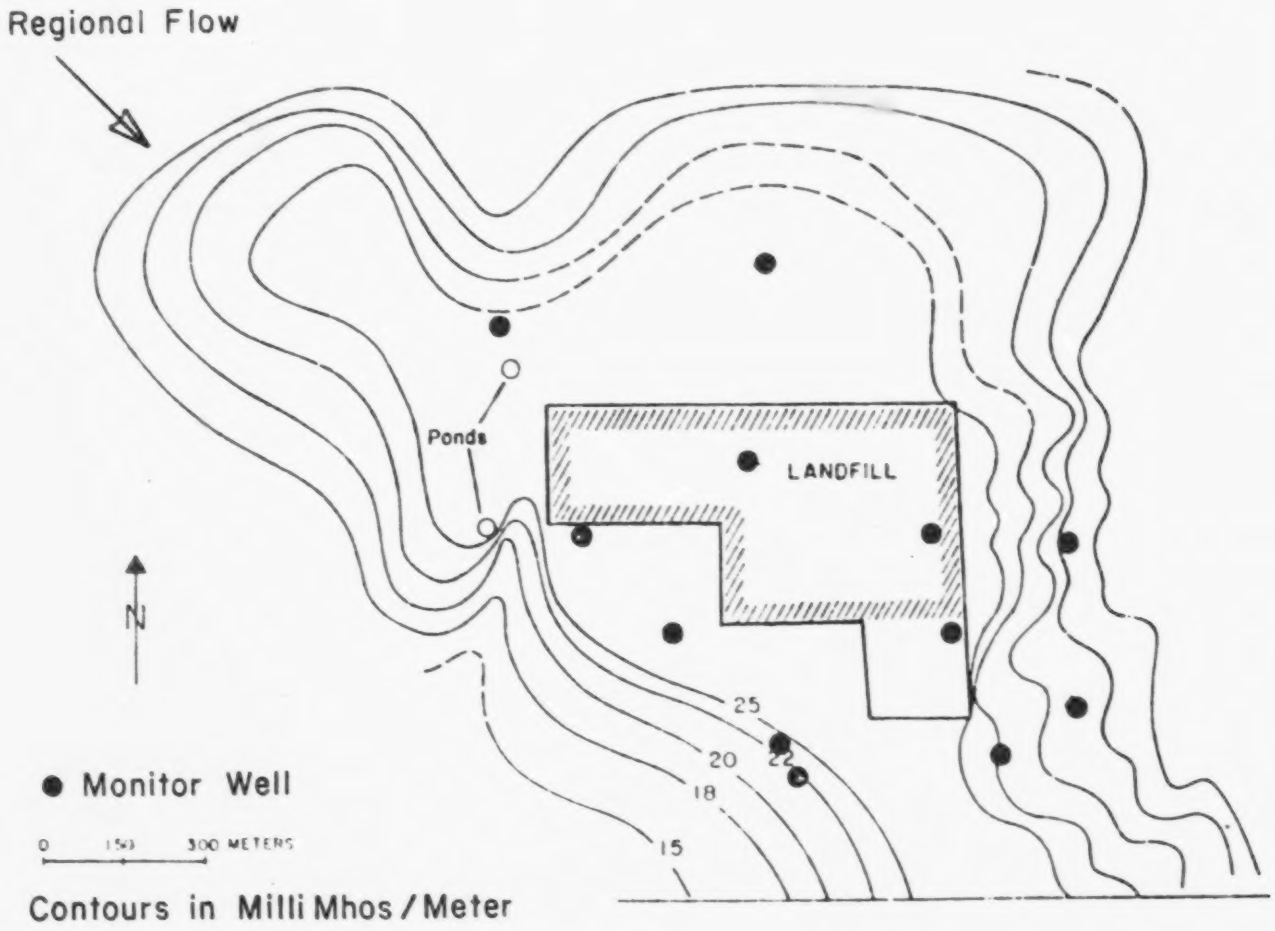

Regional Flow
Ponds
LANDFILL
N
25
22
20
18
15
● Monitor Well
0
150
300 METERS
Contours in Milli Mhos / Meter

Figure A-9. EM contour map of conductive plume at a depth of 30 meters. (Glaccum, Benson and Noel, 1981)

These pumping operations were, in effect, pulling contaminated ground water from the waste site and recycling the leachate-rich water on land northwest of the site.

In a second field study, high density EM measurements were used in concert with resistivity measurements to gather data mapping the time sequence of a leachate plume migration from a hazardous waste impoundment. Figure A-10 shows the rapid growth and response of the leachate plume over a four-year period. The site was situated in an unconfined sole-source aquifer composed of layers of sand, sandy limestone, and dense limestone to a depth of approximately 30 meters. The presence of the plume was initially detected in 1977 by conventional well monitoring techniques. A geophysical survey was performed at that time to evaluate the extent of this problem. Monitoring wells installed on the basis of the 1977 geophysical surveys have continued to mark the progress of the plume over time.

These case histories confirm the value of EM techniques as a site assessment tool, both to give guidance in positioning monitoring wells and in defining the extent of leachate plumes. The ability to provide comprehensive site coverage unobtainable by monitoring wells makes this an attractive first-go tool at the outset of any site survey.

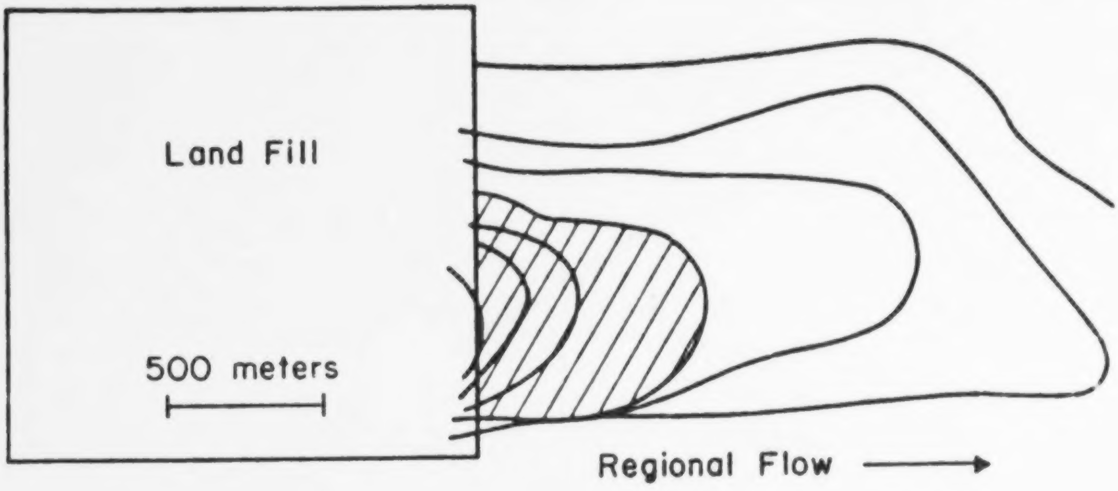
Field equipment is readily available, at reasonable cost. Field surveys can be conducted quickly and easily. Although raw EM data can often be utilized for preliminary assessment in the field, further data processing provides significant benefits. Benson [36] lists these benefits as: spatial corrections of data, removal of cultural features, filtering, obtaining statistical data, plotting of composite sets of data, three-dimensional perspective views, and contour maps (see Figure A-11).

EM-VLF Techniques

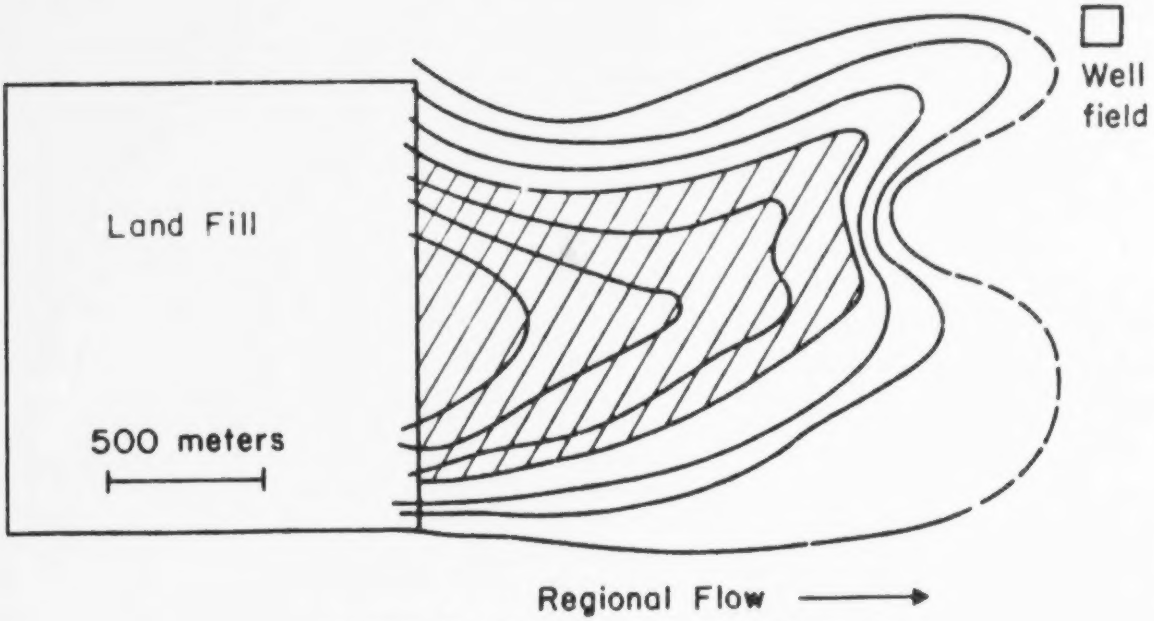
Other electromagnetic techniques that have been applied in the field include various EM-very low frequency (EM-VLF) techniques, which are used for mineral prospecting. These techniques have been applied, at least once, to evaluate the presence and extent of leachate plume migration.

Very Low Frequency (10-20 kilohertz) Navy communication transmitters radiate unmodulated carrier waves and are located at various sites around the globe. It should be noted that the term "very low frequency" refers to radio technology and is somewhat misleading when applied to the field of geophysical prospecting, since these frequencies are not low in the context of electromagnetic methods.

At great distances from the transmitter, the angle of the electric or magnetic field relative to the direction of travel varies depending on the electrical conductivity or magnetic permeability of the material through which it is traveling. The depth of material that affects the wave angle is a function of the skin depth which in turn is a function of the bulk electrical and magnetic properties of the ground and the reciprocal of the frequency being used.


Land Fill
500 meters
Regional Flow

EXTENT OF LEACHATE PLUME IN 1977


Well field
Land Fill
500 meters
Regional Flow

EXTENT OF LEACHATE PLUME IN 1981

Figure A-10. Growth of leachate plume over four-year period. (Glaccum, Benson and Noel, 1981)

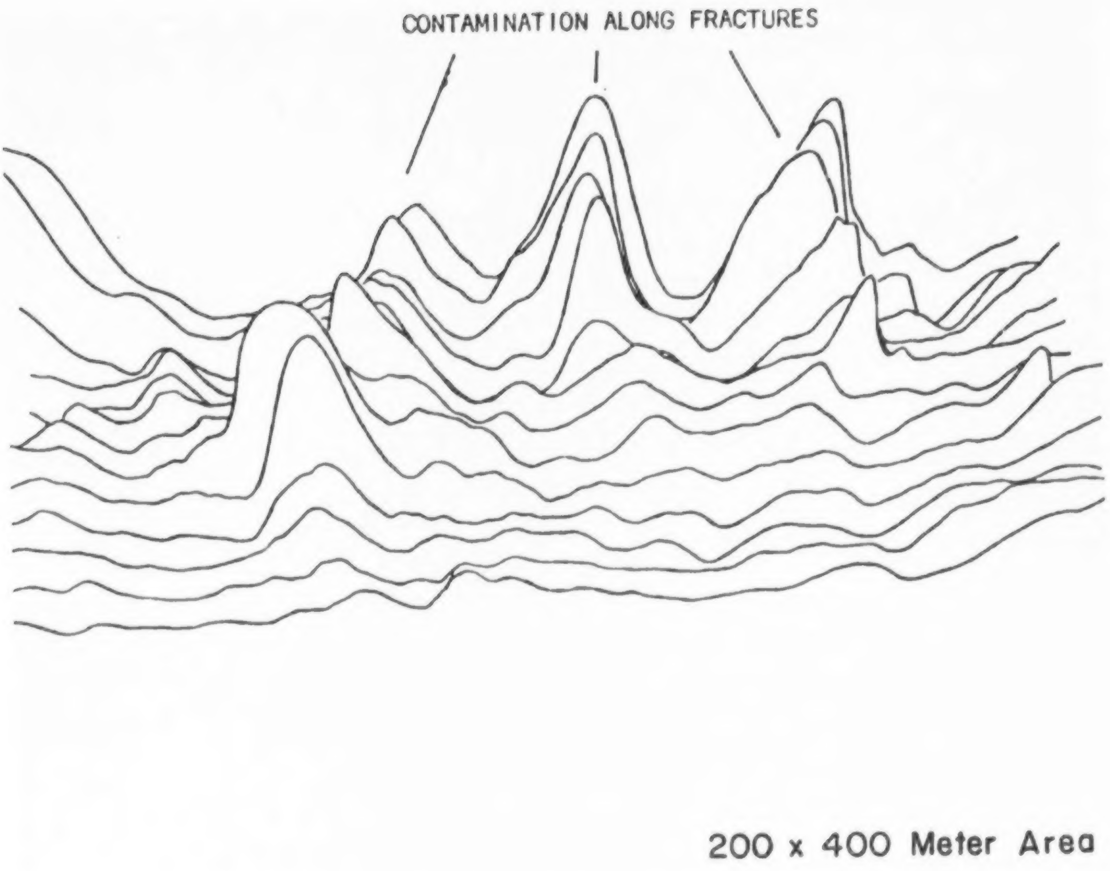


Figure A-11. Parallel EM profiles showing conductivity versus position. The high conductivity areas are caused by contaminated ground water in fractured limestone. (Glaccum, Benson and Noel, 1981)

Typically the effective depth of influence varies from about 100 meters to 1 meter over this frequency range. Very conductive surface layers will decrease the actual depth of penetration. The survey techniques vary depending on the frequency and equipment being used. The field techniques are similar and usually simpler than resistivity surveys. Typically grid lines are profiled in which a map of conductivity on the grid is obtained. Using different frequencies permit a map of conductivity versus depth to be obtained.

VLF techniques were employed by Greenhouse and Harris [37] at an abandoned waste site in southwestern Ontario as a reconnaissance tool to evaluate the extent of a leachate plume. This technique was one of several geophysical tools employed in an evaluation of the site testing the efficacy of a composite of remote sensing techniques. Because saturated overburdened

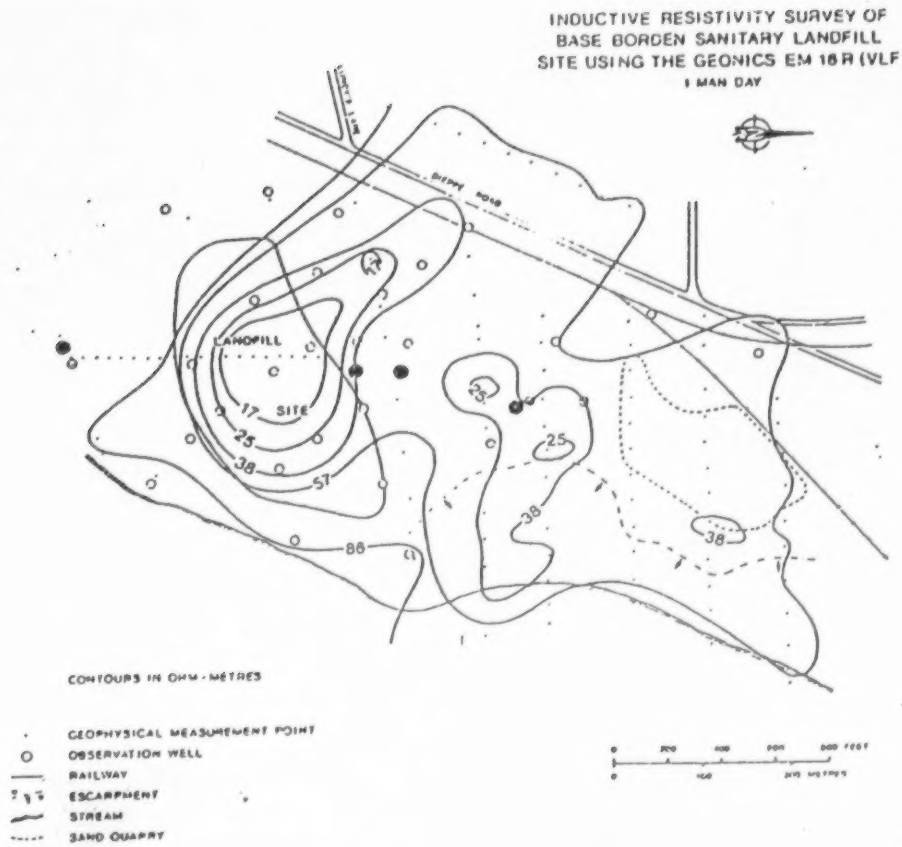

INDUCTIVE RESISTIVITY SURVEY OF
BASE BORDEN SANITARY LANDFILL
SITE USING THE GEONICS EM 16R (VLF)
1 MAN DAY
DIEPPE ROAD
LANDFILL
SITE
17
25
38
57
88
25
25
38
38
CONTOURS IN OHM-METRES
GEOPHYSICAL MEASUREMENT POINT
OBSERVATION WELL
RAILWAY
ESCARPMENT
STREAM
SAND QUARRY
0
200
400
600
800 FEET
0
100
200 METRES

Figure A-12. Contoured data - EM/VLF techniques.
(Greenhouse and Harris, 1980)

materials in this area have resistivities typically in the range of 30 ohmmeters, VLF penetration could be expected to be effective to depths of 20 meters. The contoured data shown in Figure A-12 clearly defined the gross character of contaminant migration along the plume. In addition, the EM-VLF technique appeared to achieve improved penetration of the uppermost unsaturated layer over resistivity techniques employed at the same site. A complete site survey was achieved in the course of one man-day.

EM-VLF techniques seem to offer a promise of success as a site evaluation tool, because of ease of application and depth of penetration. However, the technique has received scant application, and additional knowledge must be gained in both application and interpretation of results before a final verdict on the technique can be rendered.

High-Frequency (HF) Techniques

High-frequency (HF) techniques, which include both pulsed and continuous wave systems, are being used in a number of site assessment applications, including mapping of geologic stratigraphy in soils; locations of subsurface anomalies such as buried drums, voids, and fractures; and delineation of soil/water and freeze/thaw interfaces. These techniques have also been used in a limited way in direct mapping of pollutants.

HF techniques operate by transmitting energy, between frequencies of 1 MHz and 1000 MHz into the ground (see Figure A-13) [38]. Part of this energy is reflected whenever it encounters a change in the complex dielectric properties of the medium. Reflections reaching the receiver are detected and amplified.

Pulsed High-Frequency Techniques

Pulsed high-frequency techniques, also referred to in the literature as Ground Penetrating Radar (GPR), operates by transmitting short pulses of radar frequency energy that are then picked up by a receiver. In pulsed systems the receiver is on only when the transmitter is off. This technique can be operated from either the surface or in transillumination (borehole-to-borehole) mode. When operated in the surface mode, a radar antenna can be manually towed over a site or pulled by a vehicle to produce a continuous mapping. In the transillumination mode, the transmitter is placed in one borehole and the receiver in a second borehole. Depending upon site configuration, borehole techniques can have some advantages over surface techniques, in that it becomes possible to look underneath a conductive overburden, or to look through material rather than to receive a reflection off the observed medium. In either case, data are acquired in the form of echo time versus horizontal position.

In selecting equipment frequency range, a compromise is made between depth of penetration and the resolution or ability to detect electrical variations close to one another. In geologic materials, the higher the frequency used, the smaller the range. Typically at frequencies at or above 1 GHz the maximum range is about 1 meter in moist geologic materials. The electrical properties tend to be temperature sensitive due to the relaxation properties of the water molecule. As the frequency is decreased into the MHz range, the depth of penetration typically increases to tens of meters but the resolution decreases. The propagation of radio energy at these frequencies is also sensitive to soil type. Typically in coarse-grained materials, such as sands and gravels, the penetration range is in tens of meters; the range decreases to about 1 meter in fine grained clays. The conductivity of the pore fluid also affects the penetration range. If the fluid has very low conductivity, such as fresh water, then the range may be about 10 meters in saturated sands, but if the fluid is conductive as in salt water then the range will decrease towards zero.

The radar technique can potentially map the extent of a conductive leachate in a resistive material very accurately, but its usefulness may be severely reduced by the waste material and the soil material in and around the site. When the pulsed radar technique works well there is no other technique to

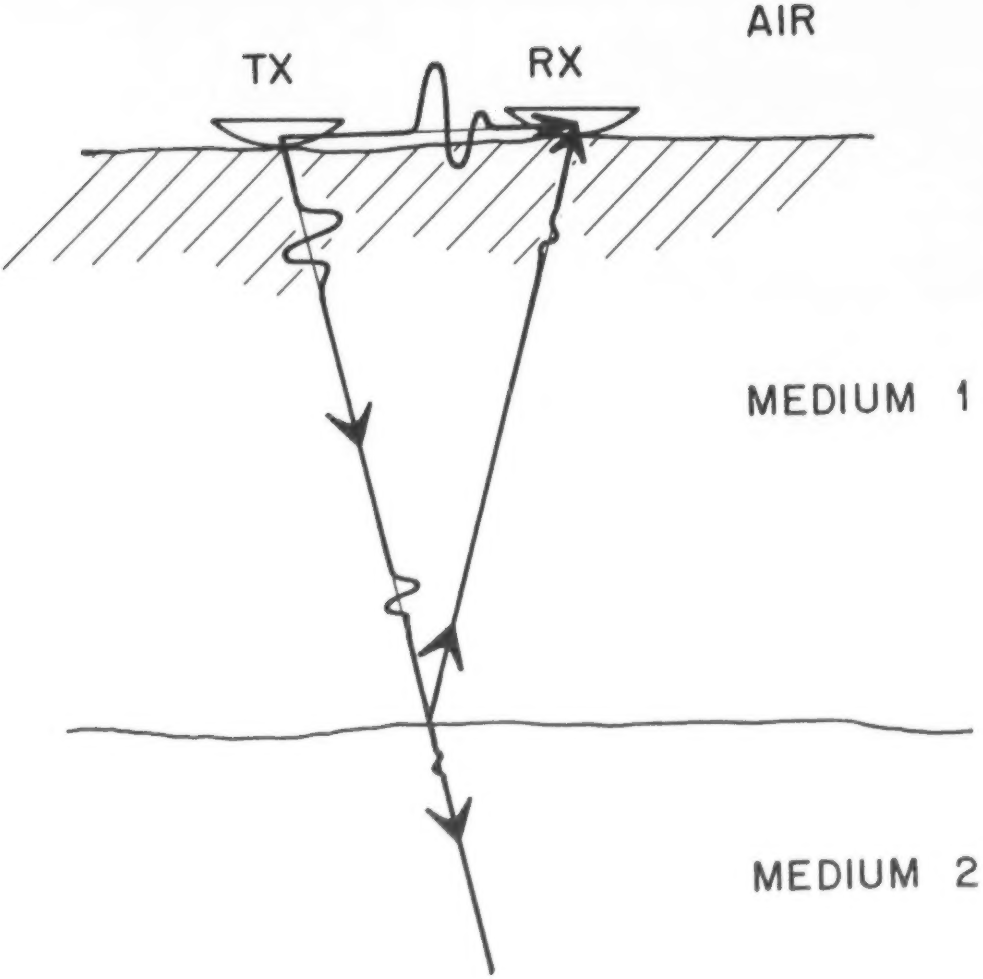


Figure A-13. Sketch of ground probing radar principles. (Davis, Scott, Morey and Annan, 1976)

compare with it, but when the geology is complicated or material is lossy (i.e., the signal is attenuated) then the interpretation is as complex as any other geophysical technique.

Continuous Wave/High Frequency Techniques (CW/HF)

The primary difference between pulsed and CW techniques is that the CW system transmit-signal is always on and the weak reflected signals from the ground must be detected in the presence of the direct signal from the transmitter. In the CW technique the data interpretation techniques are significantly more complex because less data are obtained than in the pulsed system. When used on the surface the CW-HF techniques have little advantage over the pulsed HF techniques.

The CW/HF technique has practical potential application when the transmitter and receiver are used in different boreholes. The main advantage to the pulsed system when used in a similar fashion is that more power can be generated in the CW system. A narrow-band receiver can also be used and thus the receiver sensitivity will be greater than a wide-band receiver.

Tomographic methods are used to construct a "picture" of the electrical properties between the boreholes. Many boreholes are necessary to construct a complete picture of the electrical variations. The interpretation techniques are complex and expensive but potentially a detailed map of the electrical variations under a waste impoundment can be obtained.

Geotomography

Geotomography is primarily a technique to assist with data interpretation of continuous wave measurements. The geotomographic techniques can also be applied to pulsed measurements. Tomographic techniques are used extensively in the medical profession to locate tumors in the brain using X-rays. The most significant practical difference between medical tomography and geophysical tomography is the inability to obtain geophysical data all around the area of interest; this restriction reduces the quality of the tomographs. Acceptable quality geotomographs have been obtained and the locations of tunnels and cavities have been mapped.

Generally the geotomographic technique has been applied to construct a picture of the electrical properties at frequencies between 1 to 200 MHz between boreholes. Measurements of relative signal amplitudes and travel times are measured at different frequencies with the transmitter and receiver at many different positions in the boreholes. Geotomograph results improve with a greater number of boreholes and greater change of depth around the area.

The interpretation procedure requires that the attenuation and apparent propagation velocity over the different paths between transmitter and receiver be measured, and an iterative process is used to calculate the electrical properties in a series of boxes between the boreholes being computed. The size of boxes is determined by the number of measurements made and the spacing between measurements made.

The precision of the electrical property measurements depends on the precision of the transmitter output power, the precision of the receiver, the electrical properties around the antennas, the spacing between the boreholes, and the number and travel distance multipaths. The pulsed systems can reduce the difficulty of interpreting the multipath reflected and refracted signals.

The literature review identified numerous uses of both pulsed and continuous wave/high-frequency techniques as a geologic mapping device and Benson and Glaccum [39] cite the use of pulsed techniques to detect subsurface anomalies such as buried drums and while Johnson, et al., used the techniques to confirm the lateral continuity of soil horizons [40], as shown in Figure A-14. Here the interface between fine sand and sandy clay loam horizons can be readily followed throughout the profile. Annan and Davis [41] report its use to measure ice thickness measurements, water depth and silt depth to bedrock at Norman Wells. A radar section is displayed and interpreted in Figures A-15 and A-16. Both the river bottom and the water/ice interfaces are well delineated. It has also been used to locate and define the presence and extent of gelled chemical grout in a research project conducted by the Federal Highway Administration [42].

Horton, et al. [43], as well as Benson and Glaccum [44] report the use of HF pulsed radar techniques in composite geophysical surveys at waste disposal sites, employing resistivity and/or electromagnetic techniques as well. Such surveys allow greater confidence to be placed in the data received than can be placed in any technique used alone. Figure A-17 shows the comparative results of EM and radar profile over a Karst area [45]. Note the correlation of EM and radar data where paleo-Karst features occur. An old sinkhole, filled with sand, is indicated at the right side of the EM data and delineated even more clearly at the right side of the radar data.

Continuous wave (CW) techniques have been employed both from the surface and from the borehole. El-Said reports the use of surface techniques to prospect for underground water in desert regions as early as 1956 [46]. Lord, et al. [47], report surface applications of CW (also called microwave techniques) for locating faults, evaluating pavement thickness, and locating subsurface anomalies. Borehole applications are currently being applied by Laine and Lytle at Lawrence Livermore Laboratory [48]. An example of geotomography data, from field evaluations of grouted soils, is shown in Figure A-18 [49].

Ground penetrating radar, or pulsed high-frequency, techniques currently allow site investigations in a variety of soils, and can give excellent resolution. Equipment costs are relatively high and require the use of trained field crews. CW techniques are still in the development stage and the costs of geotomography surveys tend to be high. The technique offers great promise at some future date.

Time-Domain Reflectometry (TDR)

Time-domain reflectometry (TDR), another pulsed high-frequency technique, deserves special note. TDR operates over a frequency range from 1 MHz to 1 GHz, but unlike the pulsed HF techniques mentioned earlier, TDR relies upon the signal propagating along a transmission line rather than radiating from an antenna. TDR is used to measure the high-frequency impedance between a pair of wires. A fast rise time pulse of energy is generated, which travels between a pair of wires and is reflected from any break in the wires, or any change in electrical properties between the wires constituting the cable. The location of an anomaly along the wires can be determined if the propagation of velocity of the pulse in the medium within the transmission line is known by measuring the travel time. Figure A-19 gives an example of the effect of discontinuities in a parallel transmission line upon the TDR response.

Reproduced from best available copy.

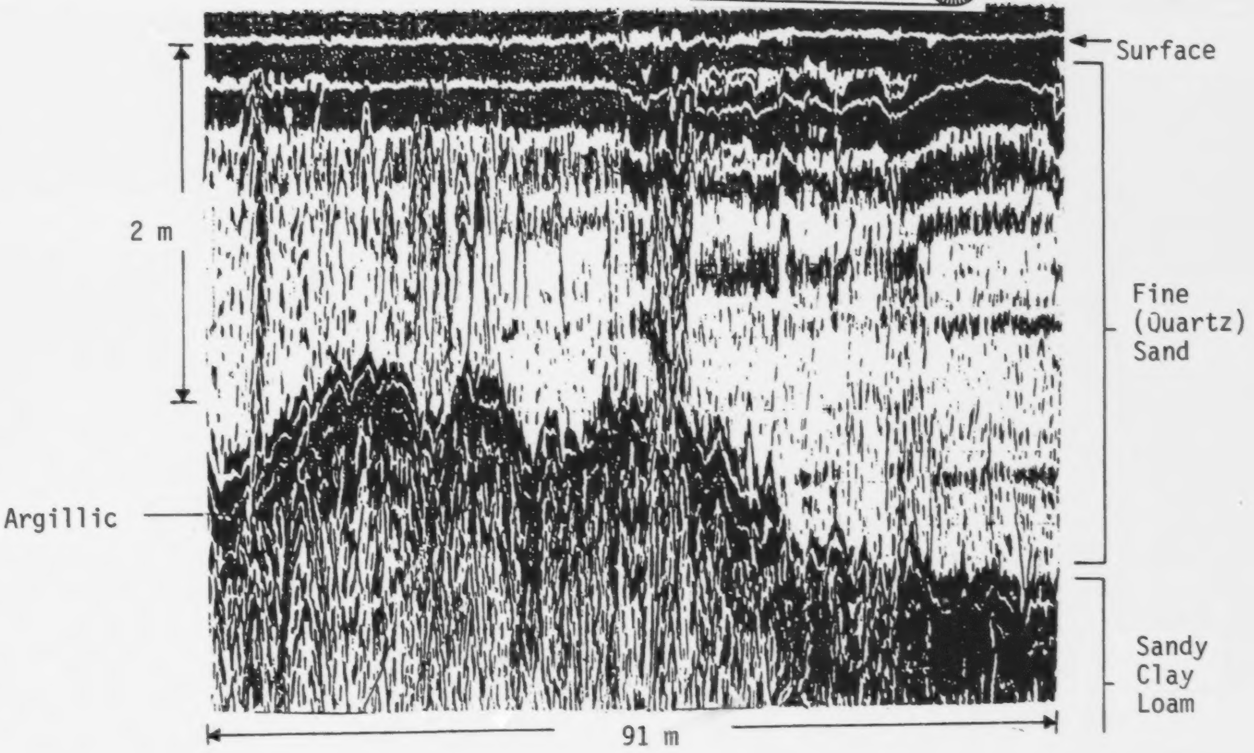


Figure A-14. Lateral continuity of soil horizon. (TECHNOS)

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 387)
TYPING GUIDE SHEET

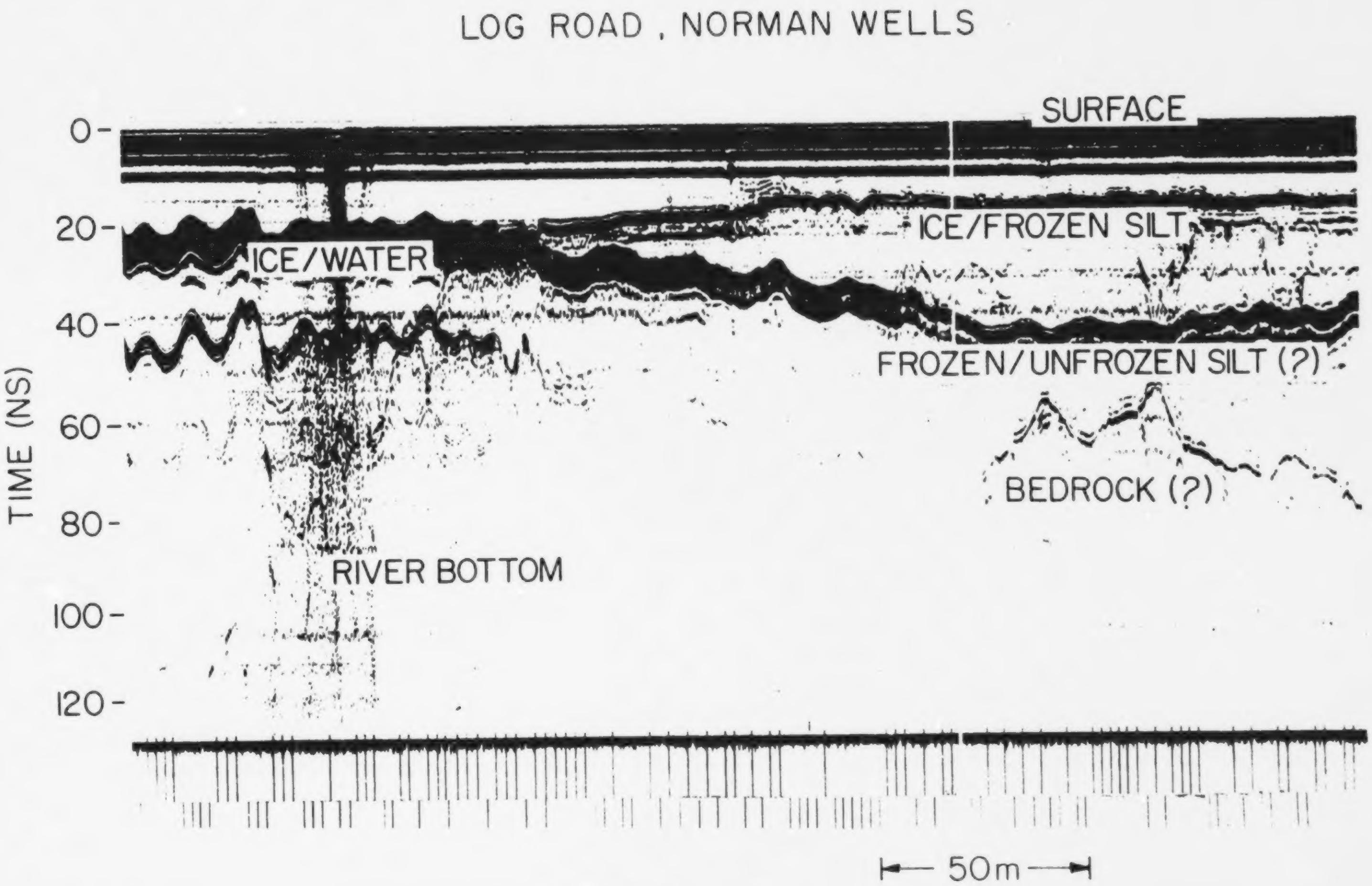


Figure A-15. Radar profile. (Annan and Davis, 1978)

EPA Form 2350-4 (4-80)
TYPING GUIDE SHEET

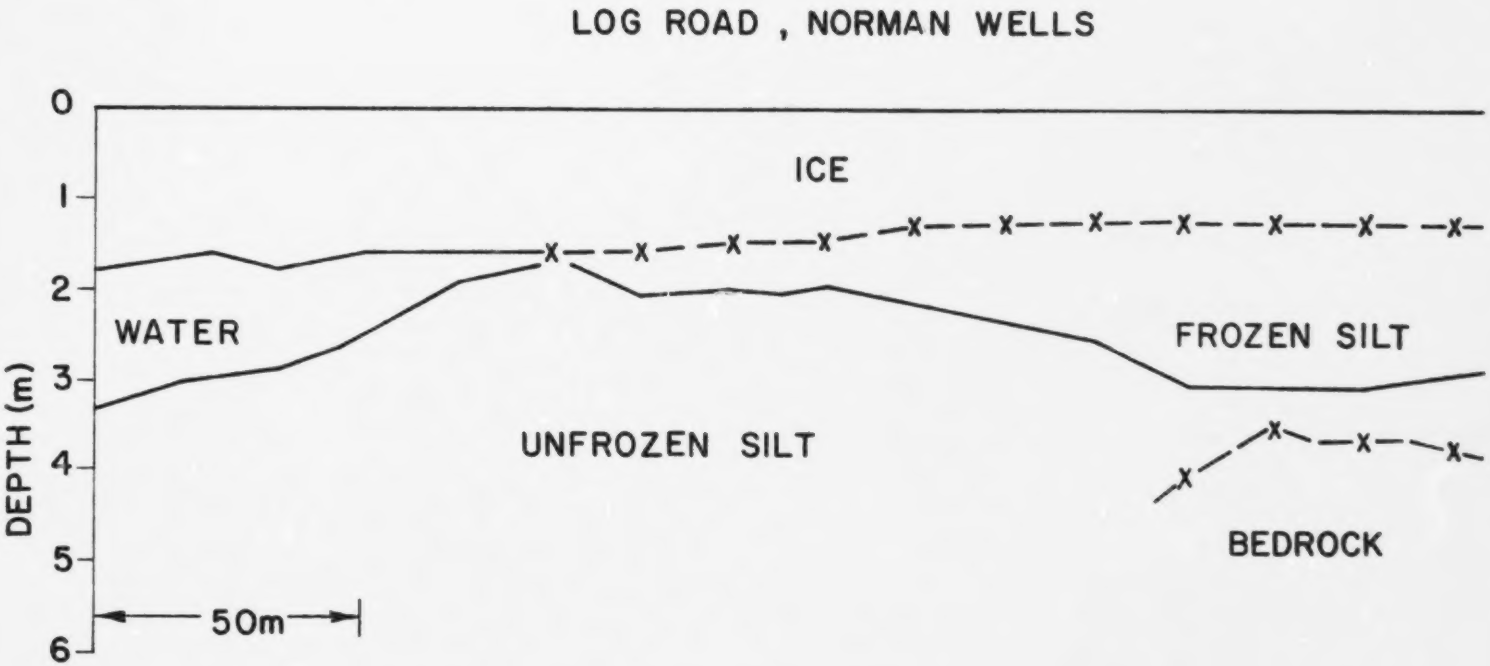
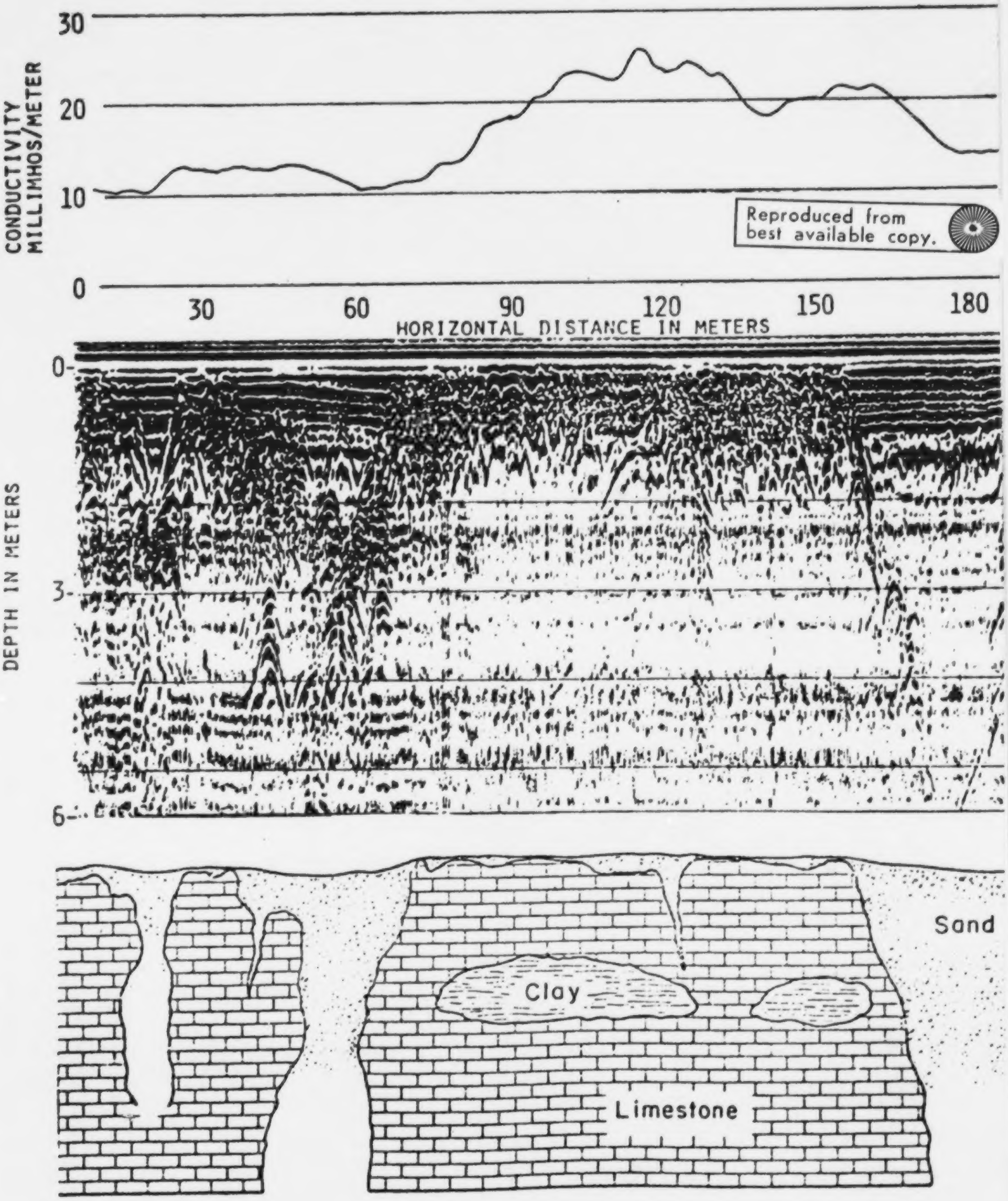


Figure A-16. Interpretation of radar profile.
(Annan and Davis, 1978)

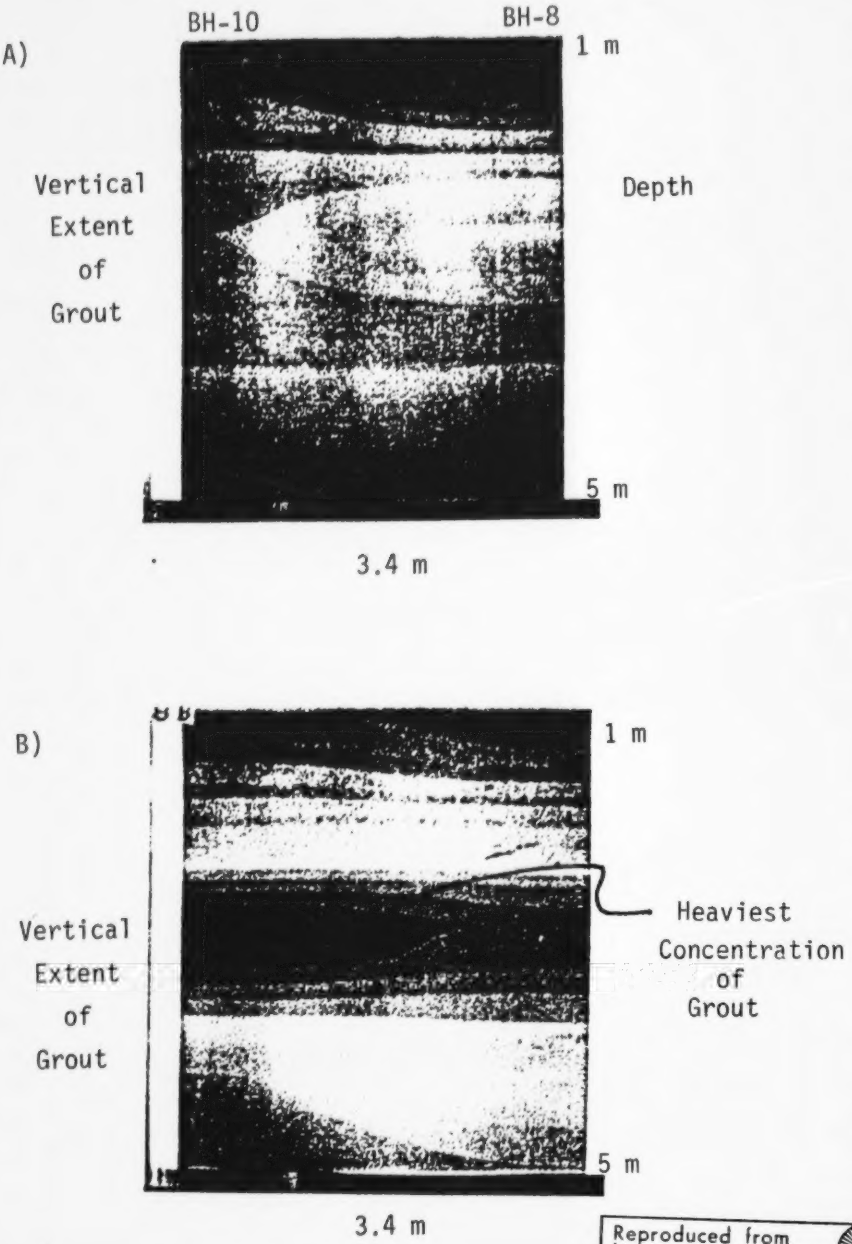
EPA Form 2350-4 (4-80)
TYPING GUIDE SHEET



Reproduced from best available copy.

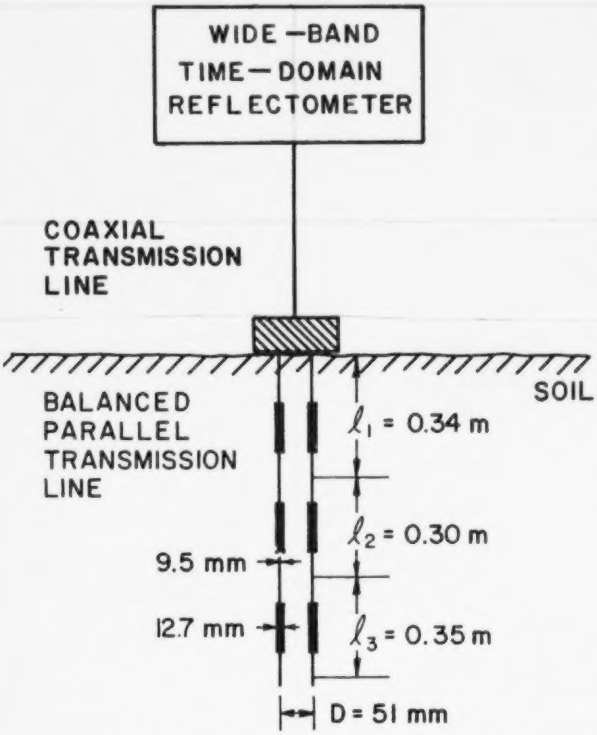
Figure A-17. EM (conductivity) and radar profiles over Karst area with geologic cross-section shown below. (Benson and Glaccum, 1979)

EPA Form 2360-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 287)
TYPING GUIDE SHEET

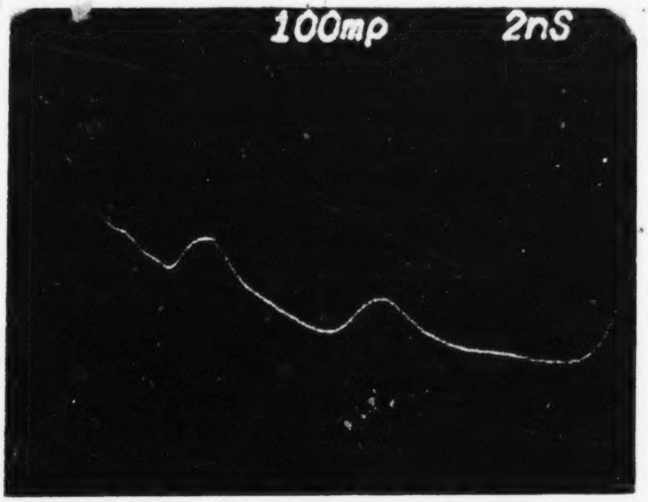

A)
BH-10
BH-8
1 m
Vertical Extent of Grout
Depth
5 m
3.4 m
B)
1 m
Vertical Extent of Grout
Heaviest Concentration of Grout
5 m
3.4 m

Reproduced from best available copy.

Figure A-18. Geotomographs showing changes in attenuation (gray levels) caused by chemical grout in a sandy soil. Boreholes 10 and 8 for two different conditions: a) after grout injection into borehole 8; and b) after grout injection into borehole 10. (Laine and Lytle, 1980)


WIDE-BAND
TIME-DOMAIN
REFLECTOMETER
COAXIAL
TRANSMISSION
LINE
SOIL
BALANCED
PARALLEL
TRANSMISSION
LINE
l_1 = 0.34 m
l_2 = 0.30 m
l_3 = 0.35 m
9.5 mm
12.7 mm
D = 51 mm

(A) Parallel transmission line using rods each with two different cross-sectional diameters.



(B) A WB TDR record of an in situ measurement using a transmission line as shown in Figure A. The positive bumps occur where the rod diameters are smaller.

Figure A-19. Effect of discontinuities in parallel transmission lines. (Davis and Chudobiak, 1975)

EPA Form 2350-4 (4-80)
(PREVIOUSLY GIN. EPA FORM 287)
TYPING GUIDE SHEET

Historically, TDR has been used to survey communication transmission lines for breaks or changes of impedance within the transmission line itself. More recently, it has been applied to the measurement of soil water content in laboratory and field experiments [50]. Wire separations of 5 cm have been used to measure the electrical properties of the soil in the cable.

Soil moisture measurement applications of TDR in the laboratory were reported by Hoekstra and Delaney [51]; Davis and Annan [52]; Davis, et al. [53]; and Topp, et al. [54]. A wide-band TDR record showing the different travel times in three similar lengths of coaxial transmission line, each filled with sand having different moisture contents, is shown in Figure A-20 [55]. As the moisture content increases, the two-way travel time increases.

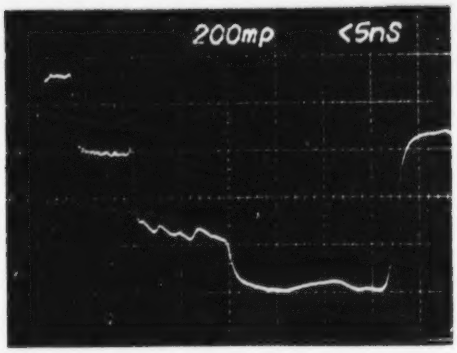
The unique capability of TDR technique to measure the electrical properties within the transmission line and to locate changes of impedance along a line make it conceptually very attractive as a leak detection technique in planned waste impoundments. Thus, like the DC resistivity gridwork discussed before, a TDR gridwork could be emplaced in or under the liner itself and monitored according to specific site needs. This technique has the capability of evaluating changes in electrical properties in the soil itself, as might be created by the presence of leachate in the ground, and such a change can be uniquely located. Thus a leak might be readily detected at one or two sites along the emplaced transmission lines, whereas a change in water table level would be reflected in many lines simultaneously. Unlike the DC resistivity gridwork, then, lines can be laid in a single orientation, and can be used even if a wire breaks. In addition, TDR transmission lines can be coated with a material similar to that employed in geomembranes, thus assuring a life expectancy equal to that of the liner itself.

It may be possible to use wire separations of about 1 meter in an actual leak detection system. To carry out the TDR measurements access to the grid wires is necessary. A pulse source and receiver must be connected to a pair of grid wires and a response of reflections versus travel time observed. Comparative measurements with time should be carried out. TDR is currently undergoing further evaluation as a leak detection technique under EPA contract No. 68-03-3030, "Development of Innovative Concepts for Detecting and Locating Leaks in Landfill Liners," by EarthTech Research Corp.

ACOUSTIC EMISSION TECHNIQUES

Acoustic emission (AE) monitoring techniques have been used for some time to evaluate rocks and metals. However, its application to soil structures is more recent. In this area it has been shown to be useful in monitoring earth stability, settlement and deformation, and water flow through earth dams. The method may also have practical application for monitoring lined waste impoundments.

Although the acoustic emission mechanism is not fully understood, it is known that sound emissions occur from structural distress and from liquid flow through a porous medium. Possibly, particles carried by a fluid through a porous medium will strike the pore walls and emit sound energy. These sounds can be monitored using a microphone-type device coupled to the ground.



LENGTH, ℓ (m)	0.33	0.32	0.32
TIME, t (ns)	2.6	6.0	9.9
MOISTURE (percent by weight)	1	8	21
RELATIVE PERMITTIVITY, ϵ_r	2.8	7.9	21.7

A WB TDR record showing the different travel times in three similar lengths of coaxial transmission line each filled with sand having different moisture contents.

Figure A-20. Comparative TDR data.

(Davis and Chudobiak, 1975)

Typically, in the field, a microphone or undamped accelerometer is coupled to the ground to monitor emissions. Sensors placed on the surface of a site may suffer from poor coupling to the ground and unwanted noise propagating through the air. In order to reduce such problems, the sensor may be coupled to a wave guide (metal rod) or placed in a borehole physically near the source of emissions.

The literature review indicated that techniques have undergone laboratory and field testing and application for several decades. Early applications of AE to measure turbulent flow through earth dams are reported by Esmiol [56] in 1971 for the Bureau of Reclamation; Crook and Coxen [57] successfully applied AE techniques to detect leakage in a Malaysian dam. In this case seepage was readily detected along the upstream face of the dam. More recent applications are reported by Koerner, et al. [58], and Huck, et al. [59], where AE techniques were used to monitor seepage from within casings placed along an axis of a leaking earth dam. In order to determine the area of the dam where seepage was greatest a flow rate test was conducted. Note the correlation between flow rates and increased acoustic emission rates displayed in Figure A-21. Koerner, et al., also reported several case histories of AE techniques applied to earth

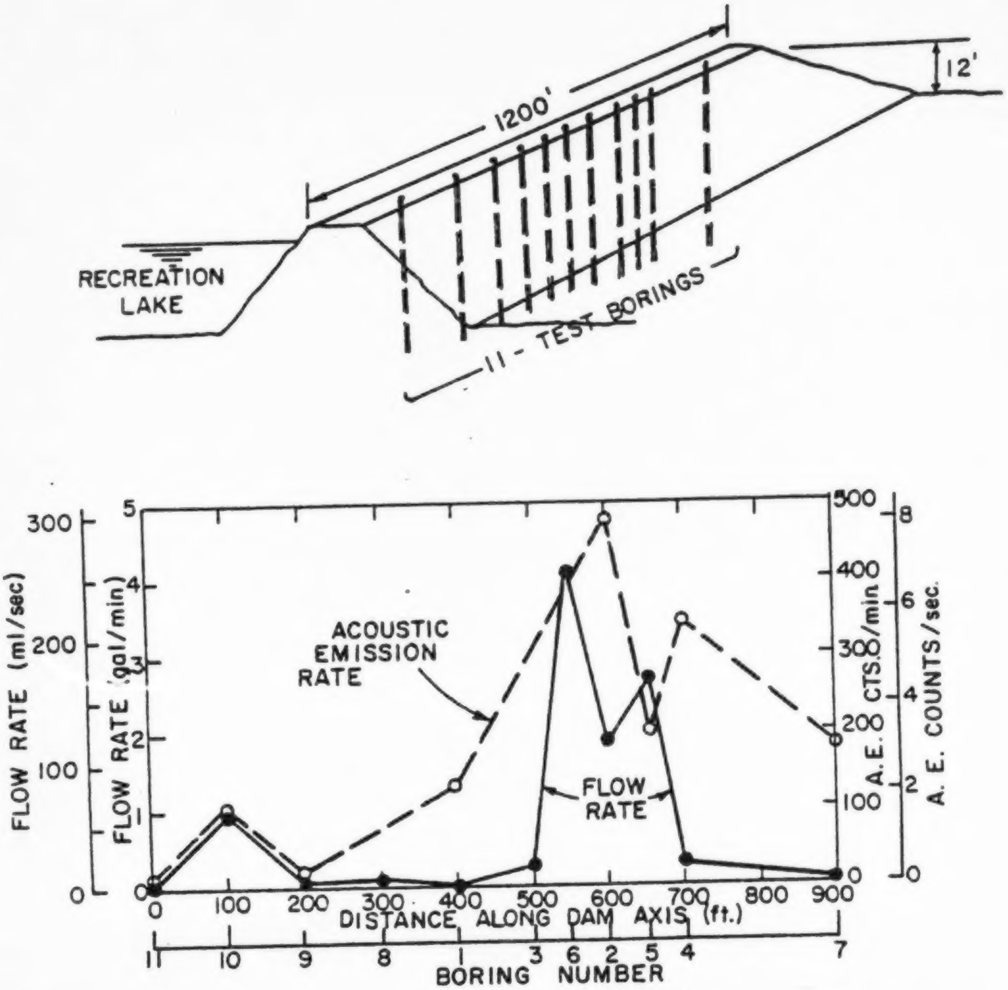


Figure A-21. Schematic diagram and flow and acoustic emission rate responses to seepage monitoring from within casing placed along axis of leaking earth dam. (Koerner, McCabe and Lord, 1981)

stability problems and settlement and deformation problems [60]. They also report the results of several small- and large-scale laboratory studies undertaken to determine the behavior of acoustic emissions in soils. Small-scale laboratory tests were undertaken to monitor both stress/strain and stress/acoustic emission responses, while systematically varying one parameter at a time. Large-scale laboratory tests were undertaken to evaluate AE applications to embankment stability, bearing capacity, and seepage problems. AE techniques have also been applied to the problem of chemical grouting in soils, where problems as to grout location and pressures at which hydrofracturing occurs often need to be resolved. Huck, et al., report the use of AE techniques to detect and control hydrofracturing during chemical grouting [61]. Figure A-22 clearly shows the

EPA Form 2350-4 (4-80)
(PREVIOUSLY EIN: EPA FORM 281)
TYPING GUIDE SHEET

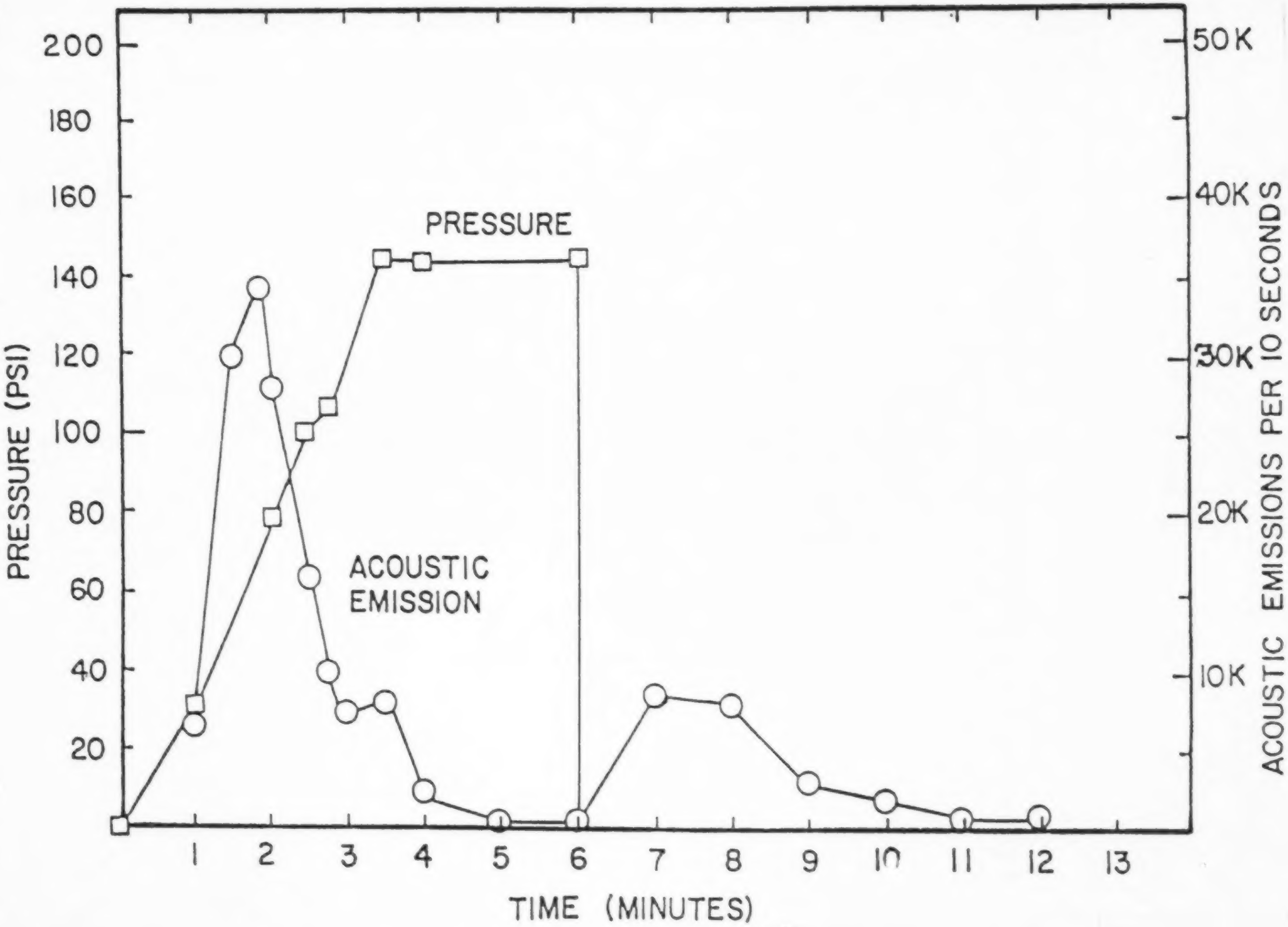


Figure A-22. Acoustic emission during hydraulic fracture. (Huck, et al.)

EPA Form 2350-4 (4-80)
TYPING GUIDE SHEET

correlation between grout pumping pressures and acoustic emission response rates.

AE techniques may have practical application for monitoring waste impoundment sites, both to detect seepage and to monitor the movement of a membrane liner undergoing stress or failure. Rapid attenuation of passive AE signals through soils make it a difficult technique to apply at existing sites. However, once the presence of a leachate plume has been determined at an existing site, it may be possible to locate it from a borehole or series of boreholes, and thus actually get close to the point source of the leak. In planned sites it may be possible to emplace a grid of transducers beneath the actual liner. It must be realized that certain acoustic emissions, occurring naturally from decomposition of the waste material or settlement and deformation of the impoundment liner, may tend to obscure emissions from seepage or liner failures. In any case, AE monitoring would need to take the form of repetitive measurements over long periods of time to establish normal background rates and to identify changes in emission rates over time.

AE monitoring techniques have an established record of field performance. However, questions as to the fundamentals of the AE process in soils remain to be answered. These include questions as to the basic mechanism causing the acoustic emissions when liquids flow through soils, under both turbulent and laminar conditions; the velocity of fluid flows necessary to cause acoustic emissions; and the propagation effects of acoustic energy in relationship to soils. In addition, questions specific to the leak detection problem need to be clarified before AE techniques can be optimally applied in the field. Thus questions as to what magnitude of flows might be expected from leaks and what flows can be heard, at what range, need further investigation. Answers to these questions will aid in understanding the theoretical aspects of the technique and will thus maximize the application of this monitoring tool.

SEISMIC TECHNIQUES

Seismic techniques have been employed for many years by the petroleum industry. They also receive wide use to map site stratigraphy. In the seismic technique energy is put into the ground. Typically the seismic source is generated either by an explosion or a hammer-type device. The seismic shock waves radiate or propagate out in hemispherical wave fronts from the source. Compressional (P) and shear (S) waves are generated. The velocities of these waves are affected by the bulk modulus or compressibility, the shear modulus or rigidity, and the density of the ground. The velocities in soils vary as a function of void volume, either air or water filled, minerology and grain size.

Sensitive receivers such as geophones on the surface will detect the signals reflected to them. The signals are then amplified and displayed on a graph showing the signals detected at the geophone versus time. If the propagation velocity to reflector is known then the depth can be calculated.

Reflection techniques, where the geophones are not spaced more than the depth to be sounded, give a good map of elastic property variations versus travel time or depth if the propagation velocity is known. Refraction techniques where the geophone spread is large compared to the depth of interest permits us to determine the propagation velocity to the reflectors and thus the depth to the reflectors.

The propagation velocity in unsaturated soils is about half that compared to the velocity in saturated soils. It is theoretically possible to detect a leak that is still in the unsaturated zone. If the leak is in the water table then there is unlikely to be any significant velocity variation and the seismic technique will not be useful for detecting the leachate plume.

The seismic technique can be used over either solid or liquid sites. At liquid sites high resolution sonar techniques can be used, making it possible to map the liner precisely. Electrical techniques will not work in conductive liquids whereas the seismic technique will.

Typically seismic techniques can be operated in three modes: from the surface, surface to borehole, and borehole to borehole.

Surface

The technique is commonly used on the surface either in the refraction or reflection mode. The geophones are placed in a line over the area to be sounded. The source of sound is usually placed at one end of the geophone string. The geophones and sound source are moved along in a line to obtain a profile of reflections versus time. In refraction sounding a graph of signals at different geophone spacings from source versus travel time is obtained permitting the propagation velocity to be determined.

Surface to Borehole

In this configuration usually the geophones are placed in the borehole at different depths and the source is moved along the surface after each series of soundings are made by moving the receivers the length of the borehole.

The results of this method give a graph of travel time versus depth. The propagation velocity versus depth can be calculated. If a change of velocity occurs due to leachate in the unsaturated zone, it may be detected.

The advantage of this method is that the signal propagates only one way through the medium; thus the range through the medium can be increased compared to the surface techniques' depth range to reflectors.

Borehole to Borehole

This method requires that both the source and receivers be put into boreholes. A graph of signal amplitude and travel time versus depth can be obtained. If a leak exists under a waste site in unsaturated soil then the signal will change and will be displayed.

Materials that have velocities that differ by a factor of 2 and that are physically at least 10 percent of the total path length should be detectable. The advantage of the borehole method is that surface effects and complex signals caused by waste material will be eliminated.

Seismic techniques have had limited application at hazardous waste sites, but largely to map site stratigraphy or to locate buried drums. Pease and James [62] note the use of seismic refraction techniques to determine depth and topography of bedrock and to determine the depth of a trench containing buried drums. Benson [63] notes that it is at least conceptually applicable to broader problems at hazardous waste sites. A conceptual study of seismic techniques to detect ground water contamination in deep well injection was undertaken by Barr [64].

INAPPLICABLE GEOPHYSICAL TECHNIQUES

In addition to the techniques already discussed as potentially applicable to leak detection in existing or planned lined sites, several techniques were briefly reviewed, and then rejected as candidate techniques. These candidates are briefly described here and the rationale for their exclusion from the ranking matrix exercise is discussed.

Thermal - Aerial

The thermal-aerial method measures temperature using IR radiation of the surface within the view of the instrument. The technique is sensitive to infrared radiation. The instrument gives a picture of the temperature of the surface viewed.

It is conceptually possible that a leak in a solid waste dump site may have a difference in temperature associated with a leak area. This could be due to the difference in thermal properties caused by a difference in leachate content or possibly caused by rising water table. It must also be noted that thermal variations will exist because of the materials in the waste site. The thermal technique might prove useful if used to look for differences of temperature over time (i.e., a number of years). However, the shallow depths at which these techniques can "see" through soils limit their usefulness to leak detection applications. Such a leak would have had to spread to such an extent that almost all other geophysical techniques as well as conventional monitoring techniques would identify it first.

Thermal - Borehole

This technique operates on much the same principles as the airborne thermal technique and is probably only useful if variations in temperature are monitored over a long period of time (i.e., many years). This measurement technique falls into the category of only "seeing" the borehole and not beyond.

Gamma

The gamma techniques, both active and passive, suffer from having limited range and essentially only monitor changes on the borehole walls. The active gamma systems measure the attenuation of gamma rays in the soil. The greater the water content or soil density the greater the attenuation to the gamma radiation.

The passive gamma systems monitor the natural gamma radiation emitted from the soil materials around the borehole. Its limitations within the borehole walls eliminate this as a leak detection technique.

Visible

The visible techniques look for changes in color associated with a leak round the walls of a borehole. Visible radiation will not look beyond the walls. Aerial photographs of a solid or liquid waste site might detect anomalous changes over a long period of time (i.e., many years). These changes may only be observed after significant damage at the site has occurred.

Neutron

In the neutron probe a beam of high-energy neutrons are emitted and a receiver detects backscattered neutrons at a lower energy level. Neutrons bombarding hydrogen atoms are scattered and lose energy to the hydrogen atoms. The technique is therefore sensitive to water and organic material. A typical range is a radius of 30 cm on all axes from the probes and varies depending on the water or organic material content.

The limited range restricts the potential of the technique for detecting leaks until they are almost at the borehole.

Magnetic Techniques

Magnetometers measure the variation of the Earth's natural magnetic field. Magnetic metals underground will show up as either distortions to the magnetic field amplitude or direction. Magnetic techniques are of greatest use for locating areas where magnetic materials such as fuel drums are located. The use of the technique for locating leachate materials is not possible unless the leachate has a magnetic property that can be detected.

Microwave Systems - Passive

Passive microwave techniques, often called radiometers, measure the radiation emitted from the surface of the ground. They measure the microwave temperature of the ground much like the thermal infrared detectors. The microwave radiometers operate typically in the gigahertz to tens of gigahertz (1 - 10 GHz) frequency range. The maximum depth of penetration is about tens of centimeters.

The technique is sensitive to temperature variations of the body observed and, thus like the thermal IR, might have some application in detecting anomalies in a waste site.

Microwave Systems - Active

The active microwave systems are similar to the high frequency, continuous wave and pulsed systems except the frequencies used are greater than 1 gigahertz. The advantages of microwave systems are that antennas can be made more directional and it is easier to construct high-resolution pulsed systems. The main disadvantage is that the relaxation frequency of the water molecule is about 10 GHz; thus much of the systems' energy is absorbed by the water molecule. The maximum penetration range in wet soils is limited to tens of centimeters. The electrical properties are also sensitive to temperature variations.

Magnetotelluric and Transient EM Techniques

Magnetotelluric and EM techniques have been considered as possible methods for detecting leaks from a waste site; both techniques are designed for deep mineral exploration applications and thus are not effective at depths down to 50 meters. The techniques are sensitive to changes in the conductivity of the ground.

The audio magnetotelluric technique which operates at higher frequencies, i.e., 10 to 1000 Hz, may be applicable, but more information is necessary. The transient EM technique has recently been undergoing significant development in Australia and Canada. The technique may offer significant potential for detecting conductive bodies below conductive overburden because the transmitter is turned off while the receiver is on, thus allowing greater receiver sensitivity than is possible with continuous wave techniques.

REFERENCES

1. Gruber, *et al.*, "Assessment of Industrial Hazardous Waste Practices: Organic Chemicals, Pesticides and Explosives Industries," EPA Report SW-1186, 1976.

2. Matrecon, Inc., *Lining of Waste Impoundment and Disposal Facilities*, Municipal Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio, Sept. 1980.

3. Miller, D.W., Ed., *Waste Disposal Effects on Groundwater*, Office of Water Supply and Office of Solid Waste Management Programs, U.S. Environmental Protection Agency, 1977 [Copyright by Premier Press, Berkeley, CA, 1980].

4. Benson, R.C., and R.A. Glaccum, "Site Assessment: Improving Confidence Levels with Surface Remote Sensing", TECHNOS, Inc., presented at the Management of Uncontrolled Hazardous Waste Sites Conference, Washington, DC, Oct. 15-17, 1980.

5. Johnson, Thomas M., Keros Cartwright, and Rudolph M. Schuller, "Monitoring of Leachate Migration in the Unsaturated Zone in the Vicinity of Sanitary Landfills," *Ground Water Monitoring Review*, Fall 1981.

6. Kays, Wm.B., *Construction of Linings for Reservoirs, Tanks, and Pollution Control Facilities*, John Wiley & Sons, 1977.

7. Parasnis, D.S., *Principles of Applied Geophysics*, Chapman and Hall Ltd., London, 1972.

8. Parasnis, D.S., 1972, *op. cit.*

9. Benson, R., R.A. Glaccum, and P. Beam, "Minimizing Cost and Risk in Hazardous Waste Site Investigations Using Geophysics", presented at the Management of Uncontrolled Hazardous Waste Sites Conference, Washington, DC, Oct. 28-30, 1981.

10. Swartz, J.H., Resistivity Studies of Some Saltwater Boundaries in the Hawaiian Islands, *Trans. Amer. Geophysics Union*, p. 387, 1937.

11. Cartwright, K. and M.R. McComas, "Geophysical Surveys in the Vicinity of Sanitary Landfills in Northeastern Illinois," *Ground Water*, 6, pp. 23-30, 1968.

12. Stollar, R.L. and P. Roux, "Earth Resistivity Surveys - A Method for Defining Groundwater Contamination," Ground Water, 13, pp. 145-150, 1975.

13. Berk, W.J., and B.S. Yare, "An Integrated Approach to Delineating Contaminated Groundwater," Ground Water, 15, pp. 138-145, 1977.

14. Fink, W.B., Jr., and D.B. Aulenbach, "Protracted Recharge of Treated Sewage into Sand, Part II - Tracing the Flow of Contaminated Groundwater with a Resistivity Survey," Ground Water, 12, pp. 219-223, 1974.

15. Klefstad, G., L.V.A. Sendlein, and R.C. Palmquist, "Limitations of the Electrical Resistivity Method in Landfill Investigations," Ground Water, 13, pp. 418-427, 1975.

16. Hackbarth, D.A., "Field Study of Subsurface Spent Sulfide Liquor Movement Using Earth Resistivity Measurements," Ground Water, 9, pp. 11-16, 1971.

17. Rogers, R.B. and W.F. Kean, "Monitoring Groundwater Contamination at a Fly Ash Disposal Site Using Surface Electrical Resistivity Methods," Ground Water, 18, pp. 472-478, 1980.

18. Kean, W.F. and R.B. Rogers, "Monitoring Leachate in Groundwater by Corrected Resistivity Methods," Bulletin of Assoc. of Engineering Geol., 18, pp. 101-107, 1981.

19. Reed, P.C., K. Cartwright, and D. Osby," Electrical Earth Resistivity Surveys Near Brine Holding Ponds in Illinois," Environment Geology, Notes #95, Illinois State Geological Survey, 30 pp., 1981.

20. Greenhouse, J.P. and R.D. Harris, "Hydrogeological Studies of a Sandy Aquifer at an Abandoned Landfill, Part 8, DC, VLF and Inductive Resistivity Surveys," Department of Earth Sciences, University of Waterloo, Waterloo, Ontario, July 1980.

21. Klefstad, G., et al., 1975, op. cit.

22. Koefoed, O., 1979,Geosounding Principles, 1, Resistivity Sounding Measurements. Elsevier Publishing Company, Amsterdam, 276 pp.

23. Davis, P.A., 1979, "Interpretation of Resistivity Sounding Data: Computer programs for solutions to the forward and inverse problems," Information Circular 17, Minnesota Geological Survey, 1633 Eustis St., St. Paul, MN 55108, 1979.

24. Rogers, R.B. and W.F. Kean, 1980, op. cit.

25. Kean, W.F. and R.B. Rogers, 1981, op. cit.

26. Zonge, R., "The Complex Resistivity Method," unpublished report, Zonge Engineering and Research Corporation, Tuscon, AZ, 1981.

27. Haines, B.M., "The Detection of Water Leakage from Dams Using Streaming Potential," SPWLA 19th Annual Logging Symposium, 1978.

28. Greenhouse, J.P. and R.D. Harris, 1980, op. cit.

29. Johnson, V.R., "Leak Detection Systems for Landfills and Impoundments," Third National Conference on Hazardous Materials Management, Anaheim, CA, 1981.

30. Benson, R.C., TECHNOS, Inc., "An Introduction to Some Surface Geophysical Methods for Hazardous Site Assessments," unpublished report, 1981.

31. Kolmer, J.R., "Investigation of the LiPari Landfill Using Geophysical Techniques," Proc. of the Seventh Annual Research Symposium, EPA-600/9-81/002, pp. 298-311, March 1981.

32. Benson, R.C., and R.A. Glaccum, "Remote Assessment of Pollution in Soil and Groundwater," presented at the Hazardous Materials Risk Assessment Disposal and Management Conference," Miami Beach, FL, April 25, 1979.

33. Benson, R.C., and R.A. Glaccum, 1979, op. cit.

34. Greenhouse, J.P., and R.D. Harris, 1980, op. cit.

35. Glaccum, R., R. Benson, and M. Noel, "Improving Accuracy and Cost-Effectiveness of Hazardous Waste Site Investigations with a New Generation of Geophysical Methods," presented at National Water Well Association, 1981, Groundwater Technology Division Education Session, Kansas City, Sept. 15-17, 1981.

36. Benson, R.C., TECHNOS, Inc., 1981, op. cit.

37. Greenhouse, J.P., and R.D. Harris, 1980, op. cit.

38. Davis, J.L., W.J. Scott, R.M. Morey, A.P. Annan, "Impulse Radar Experiments on Permafrost near Tuktoyaktuk, Northwest Territories," Canadian J. of Earth Sciences, V. 13, No. 11, p. 1584-1590, 1976.

39. Benson, R.C., and R.A. Glaccum, "Radar Surveys for Geotechnical Site Assessment," presented at ASCE Convention, Atlanta, GA, Oct. 23-25, 1979.

40. Johnson, R.W., R. Glaccum, and R. Wojtasinski, "Application of Ground Penetrating Radar to Soil Survey," Soil and Crop Science Society of Florida Proceedings, Vol. 39, Oct. 2-4, 1979.

41. Annan, A.P., and J.L. Davis, "High Frequency Electrical Methods for the Detection of Freeze-Thaw Interfaces," presented at the Third International Conference on Permafrost, Edmonton, Alberta, Canada, July 20-13, 1978.

42. Hayward Baker Co., EarthTech Research Corp. and ENSCO, Inc., "Chemical Soil Grouting Improved Design and Control," Final Report to Federal Highway Administration, McLean, VA, Contract No. DOT-FH-11-9397, Dec. 1980.

43. Horton, K.A., R.M. Morey, L. Isaacson, and R.H. Beers, "The Complementary Nature of Geophysical Techniques for Mapping Chemical Waste Disposal Sites: Impulse Radar and Resistivity," Geo-Centers, Inc., Proc. of Conf. on Control of Hazardous Materials Spills, Washington, D.C., Oct. 28-30, 1981.

44. Benson, R.C., and R.A. Glaccum, 1979, op. cit.

45. Benson, R.C., and R.A. Glaccum, 1979, op. cit.

46. El-Said, M.A.H., "Geophysical Prospecting of Underground Water in the Desert by Means of Electromagnetic Interference Fringes," Proc. of the Institute of Radio Engineers, V. 44, No. 1, pp. 24-30, Jan. 1956.

47. Lord, A.E., Jr., R.M. Koerner, and J.S. Reif, "Determination of Attenuation of Penetration Depth of Microwaves in Soil," Geotechnical Testing J., Vol. 2, No. 2, June 1979.

48. Laine, E.F., R.J. Lytle, and J.T. Okada, "Cross-Borehole Observation of Soil Grouting," J. of the Geotechnical Engineering Div., Proc. of the American Society of Civil Engineers, V. 106, No. GT8, pp. 871-875, 1980.

49. Hayward Baker Co., et al., 1980, op. cit.

50. Topp, G.C., and J.L. Davis, "Detecting Infiltration of Water Through Soil Cracks by Time Domain Reflectometry," Geoderma, Vol. 26, pp. 13-23, 1981.

51. Hoekstra, P. and A. Delaney, "Dielectric Properties of Soils at UHF and Microwave Frequencies," J. of Geophys. Res., 79:1699-1708, 1974.

52. Davis, J.L., and A.P. Annan, "Electromagnetic Detection of Soil Moisture: Progress Report I," Can. Jour. of Remote Sensing, 3:76-86, 1977.

53. Davis, J.L., G.C. Topp, and A.P. Annan, "Electromagnetic Detection of Soil Water Content: Progress Report II", Proc. of Remote Sensing of Soil Moisture and Groundwater, Workshop, Canadian Aeronautics and Space Institute, Ottawa, Nov. 1976, p. 96-109, 1977.

54. Topp, G.C., J.L. Davis, and A.P. Annan, "Electromagnetic Determination of Soil Water Content: Measurements in Coaxial Transmission Lines," Water Resources Research, 16:574-582, 1980.

55. Davis, J.L., and W.J. Chudobiak, "In-Situ Meter for Measuring Relative Permittivity of Soils," Paper 75-1A, Geol. Surv. Can., Ottawa, pp. 75-79.

TYPING GUIDE SHEET

56. Esmiol, E.E., "Field Evaluation of the Microacoustic Detector at Senator Wash Reservoir," Report to U.S. Bureau of Reclamation, Denver, CO, July 30, 1971.

57. Crook, D.E., and R.E. Coxon, Proc. of Second Congress in Large Dams, Q. 45, R. 30, Mexico, pp. 527-540, 1976.

58. Koerner, R.M., W.M. McCabe, and A.E. Lord, State-of-the-Art Lecture: Acoustic Emission Behavior and Monitoring of Soils," A.S.T.M. Symposium on Acoustic Emission in Geotechnical Engineering Practice, Detroit, MI, June 1981.

59. Huck, P.J., W.H. Baker, M.J. Waller, and J.C. Fowler, Monitoring Cement Grouting in Rock, Final Report for Federal Highway Admin. and Bureau of Reclamation Contract No. DOT-FH-11-9397.

60. Koerner, R.M., W.M. McCabe, and A.E. Lord, 1981, op. cit.

61. Huck, P.J., R.M. Koerner, and M.J. Waller, Effects of Injection Pressure During Chemical Grouting. Report for Baltimore MTA and U.S. Department of Transportation, UMTA, to be published.

62. Pease, R.W., Jr., and S.C. James, "Integration of Remote Sensing Techniques with Direct Environmental Sampling for Investigating Abandoned Hazardous Waste Sites," National Conf. on Management of Uncontrolled Hazardous Waste Sites, Washington, D.C., Oct. 28-30, 1981.

63. Benson, R.C., 1981, op. cit.

64. Barr, F.J., "Feasibility Study of a Seismic Reflection Monitoring System for Underground Waste Material Injection Sites," Second Int'l Symposium on Undergound Waste Management and Artificial Recharge, 1973.

APPENDIX B

ANNOTATED BIBLIOGRAPHY

1. Annan, A.P., and J.L. Davis, "High Frequency Methods for the Detection of Freeze-Thaw Interfaces," Proc. of the Third Int'l Conf. on Permafrost, Edmonton, Alberta, Canada, V. I, pp. 496-500, July 10-13, 1978.

   Descriptors: Clay / Dielectric Constant / Freezing / Ground Water / Ice-Water Interfaces / Radar / Sand / Soil Tests / Temperature / Time-Domain Reflectometry.

   Field observations of permafrost (geologic materials perennially at 0°C or lower) show that the dielectric constant indicates the state of pore water and that shallow freeze-thaw boundaries can be mapped from the surface. The electrical properties of geologic materials in the frequency range of 10 to 1,000 MHz are strongly dependent on the unfrozen water content. The real dielectric constant in this frequency range is primarily determined by the water content and only weakly dependent on other variables including soil type.

2. Barr, F.J., Petty-Ray Geophysical Group, "Feasibility Study of a Seismic Monitoring System for Underground Waste-Material Injection Sites," Second Int'l Symp. on Underground Waste Management and Artificial Recharge, 1973.

   Descriptors: Waste Materials / Ground Water / Nondestructive Testing / Seismic Reflection / Leak Detection / Instrumentation Equipment / Data Interpretation / Monitoring Systems / Field Technique.

   This paper presents a feasibility study of the applicability of seismic reflection techniques to monitor the movement and distribution of injected waste materials. The seismic reflection technique involves the introduction of acoustic energy into the earth from the surface, and the recording of signals that are indicative of the travel time and amount of energy reflected from each of many closely-spaced points along each subsurface formation. The author proposes the use of this method on a periodic basis to detect changes of acoustical properties in the receiving formation and surrounding formation to monitor effectively the movement and position of waste materials.

The author discusses field technique, field equipment, and data interpretation. However, at the time of this article, the technique, though widely used in petroleum exploration, had not been applied to the problem of waste site monitoring.

3. Benson, R.C., and R.A. Glaccum, "Radar Surveys for Geotechnical Site Assessment," presented at American Society of Civil Engineers Convention, Atlanta, GA, Oct. 23-25, 1979.

Descriptors: Site Investigation / Subsurface Borehole / Ground Probing Radar (GPR) / Instrumentation / Data Presentation / Leak Detection / Seepage Data Interpretation / Ground Water / Subsidence.

This paper presents a review of the applications and limitations of ground probing radar (GPR) as a geotechnical site assessment tool. The authors conclude that although GPR is a shallow, site specific tool, it can often detect and map a variety of soil and rock features including cementation, clays, organics, sediment layering, water infiltration zones, subsidence, depth to rock, and other rock and karst features. In addition, GPR can detect buried containers as well as locate and follow the course of pollutants in the ground. The penetration range decreases as the electrical conductivity of the ground increases. Factors that typically increase the electrical conductivity are fine grain soils (silts or clays), or salts in the soil water. The report presents several examples of GPR data. The authors note that these examples were chosen for appropriateness and clarity, and are not necessarily representative of average data gathered in the field.

4. Benson, R.C., and R.A. Glaccum, "Remote Assessment of Pollution in Soil and Ground Water," Hazardous Material Risk Assessment Disposal and Management Conf., Miami Beach, FL, April 25, 1979.

Descriptors: Electromagnetic (EM) Techniques / Ground Penetrating Radar (GPR) / Landfills / Seepage / Leak Detection / Leachate / Hydrogeology, Ground Water / Contamination / Data Presentation / Surface.

This paper describes the application of low-frequency electromagnetic conductivity techniques and high-frequency ground probing radar techniques to the remote assessment of pollutants leaching from waste impoundments. Both techniques performed well in assessing diverse site conditions; however, both techniques are site specific and the authors note that they do not work well under all site conditions. The EM techniques were used successfully at two sites to map the extent and direction of flow of leachate from the site into the ground water. The EM techniques were successful despite the presence of trash and waste at the sites which could have posed significant "noise" problems. GPR techniques described herein were used primarily as soil assessment tools.

The authors recommend a multi-disciplinary approach to site assessment, especially to solve more complex problems. Further, these methods do not provide a unique solution in themselves. They require a professional knowledge of geology, hydrology, geophysics, geochemistry, etc., as well as familiarization with local site conditions to make meaningful interpretations. They conclude that for maximum economic benefits, these methods should be applied in site studies early in the program, especially before extensive (and expensive) drilling or other work has been performed. The results of these surveys would dictate the optimum position of test wells and allow the investigator to use the sample data with a high level of confidence.

5. Benson, R.C., and R.A. Glaccum, "Site Assessment: Improving Confidence Levels With Surface Remote Sensing," TECHNOS, Inc. Presented at the Management of Uncontrolled Hazardous Waste Sites Conf., Washington, DC, Oct. 1980.

Descriptors: Hazardous Waste Sites / Hydrogeology / Site Assessments / Ground Penetrating Radar (GPR) / Electromagnetic (EM) Technique / Magnetics / Metal Detection / Leachate Plumes.

A number of remote sensing techniques are reviewed briefly comparing cost versus technical results. The techniques include airborne, surface and borehole methods. Four methods of continuous geophysical surveys are discussed, showing their application to hazardous waste site assessment and comparing the degree of confidence levels achieved by each technique. Surface techniques examined include ground penetrating radar, electromagnetics, metal detectors and magnetics. The data include high resolution surveys of natural site conditions as well as assessment of buried steel drums. The authors conclude that the data (and confidence level) in these examples could not have been obtained by conventional monitoring or drilling techniques. The authors' experience indicates that utilizing these various geophysical methods in an integrated approach allows a rapid convergence of information, thereby defining site variables, and indicating the direction for an optimal drilling and direct sampling program.

6. Benson, R.C., R. Glaccum, and P. Beam, "Minimizing Cost and Risk in Hazardous Waste Site Investigations Using Geophysics". Presented at the Management of Uncontrolled Hazardous Waste Sites Conf., Washington, DC, Oct. 1981.

Descriptors: Hazardous Waste Sites / Site Assessments / Leachate Plumes / Leak Detection / Geophysical Techniques / Hydrogeology / Ground Water Flow Monitoring.

This paper discusses some of the problems, variables, errors, and risks encountered in hazardous waste site evaluation. Cost effectiveness of geophysical remote sensing assisted programs are compared to traditional drilling and sampling methods. The authors conclude that the number and placement of monitor wells are often inadequate to describe the natural geohydrologic setting, evaluation of burial sites, or contaminant plumes from hazardous waste sites. As a result, significant errors are made in assessing conditions due to a lack of adequate spatial information.

As the size of the target decreases and the complexity, details and overall site size increase, the cost benefit of a geophysics-assisted systems approach becomes more significant. Authors conclude that alternatives to direct sampling are available to optimize hazardous waste site assessments using geophysical sensing techniques.

7. Berk, W.J., and B.S. Yare, "An Integrated Approach to Delineating Contaminated Ground Water," Ground Water, V. 15, pp. 38-45, March-April 1977.

Descriptors: Ground Water Contamination / Monitoring Wells / Leak Detection / Hydrogeology / Waste Impoundment / Landfill / Hazardous Waste / Site Assessment / Wenner Array / Resistivity Techniques.

Disposal of industrial process water into an unlined lagoon in permeable Atlantic Coastal Plain sediments resulted in a ground water contamination problem caused by infiltration of the process water into a major unconfined aquifer which underlies the lagoon at shallow depth. Most of the area water-supply wells terminate in this formation. Before this disposal method was discontinued, traces of the process water appeared in nearby water wells.

Because of the relatively large area and depths involved, as indicated by preliminary data, delineation of the distribution of contaminant within the aquifer through a systematic well drilling program posed a significant economic problem. To keep costs within a reasonable range, a resistivity survey program was implemented to obtain information on the gross distribution of the contaminant and to provide data for the selective location of monitor wells. Eight wells were constructed to obtain samples of the ground water in order to measure contaminant concentrations and to verify the interpretations of areal contaminant distribution inferred from the resistivity data. The ground water sampling procedure developed during this investigation is described.

The combination of the resistivity survey with the ground water sampling procedure developed during this investigation proved a reliable technique for delineating in three dimensions a contaminant body within an aquifer in unconsolidated sediments. Utilization of the resistivity survey data to selectively place the monitor wells and to define the lateral extent of the contamination increased the efficiency of the investigation and significantly reduced the cost of the program.

8. Cherkauer, D.S., "The Effect of Flyash Disposal on a Shallow Ground Water System," Ground Water, V. 18, No. 6, pp. 544-50, Nov-Dec 1980.

Descriptors: Ground Water / Contamination / Leachate Plume Monitoring / Piezometers / Hydrogeology.

At a flyash landfill in southwestern Wisconsin, dry ash was placed directly in contact with a shallow sand and gravel aquifer. Substantial modification of ground water quality occurred, primarily by sulfates, calcium and magnesium. However, after eight years the contamination spread less than 200 meters from the site in a permeable aquifer. In addition, toxic metals contained in the ash proved quite immobile in the ground water. Fortuitous location of the disposal site in alkaline sediment upflow from ground water discharge in a marsh appears to have limited the extent of contamination. The site was monitored over a period of five years, using conventional ground water quality monitoring techniques.

9. Daniels, J.J., and J.H. Scott, "An Experiment to Test Hole-to-Hole Resistivity Measurements for Locating Mine Openings in Coal Seams," U.S. Department of the Interior, Geological Survey, Open-File Report 80-895 (Preliminary Report), 1980.

Descriptors: Resistivity Anomalies / Resistivity / Borehole / Instrumentation / Field Technique / Data Interpretation.

Hole-to-hole resistivity was used in the field for detection of mine openings in a coal seam. Hole-to-hole direct current resistivity measurements were made by placing a current source in a borehole and measuring the resulting potential difference between two electrodes in an adjacent borehole. Boreholes were spaced at an average distance of 91.5 m. This technique was shown to be useful in detecting and interpreting resistivity anomalies located too far away from a borehole to be detected with conventional well-logging probes. Several sets of measurements from different pairs of source-receiver holes were necessary to qualitatively define the location of the mine workings.

10. Daniels, J.J., and J.H. Scott, "Hole-to-Surface Resistivity Measurements at Salt Valley, Utah," U.S. Department of the Interior, Geological Survey, Open File Report 80-981, 1980.

Descriptors: DC Resistivity Techniques / Geophysical Surveys / Hole-to-Hole / Hole-to-Surface / Detection Methods / Field Techniques / Data Interpretation / Geologic Investigations.

Hole-to-surface, direct-current resistivity measurements were used to test the feasibility of applying this technique to detect geologic inhomogeneities in evaporites at Salt Valley, Utah. The study indicated that (1) the heterogeneous nature of the caprock in the area combined with line-source electric field excitation from the steel casings caused a multi-directional distribution of the electric fields measured at the surface; and (2) differences in the response along the same profile for different source depths might be the result of changes in the current distribution caused by interbeds in the area surveys. Measurements made parallel and perpendicular to the valley walls allowed a comparison of variations in the halite caprock interface. The authors conclude that total field mapping would be more useful than the single-component data collected in this study.

This technique offers some applications to monitoring changes in waste sites, particularly in conjunction with other surface techniques. More work will be necessary to determine its actual usefulness.

11. Davis, J.L., "Relative Permittivity Measurements of a Sand and Clay Soil In-Situ," Paper 75-1C, Geol. Surv. Can., Ottawa, pp. 361-65, 1975.

Descriptors: Clay / Dielectric Constant / Ground Water / Permittivity / Soil Moisture Content / Soil Tests / Heat / Thermocouples / Time-Domain Reflectometry (TDR).

Wide band TDR is used to measure moisture content over depths of one and two meters. Data show relative permittivity and moisture content as a function of time for a nine-month period. Effects of precipitation and freezing are seen. Discontinuities in the rod diameters are used to give depth markers.

$$E_r = (3x10^8)t^{2/L}$$

Thermocouples measure soil temperature. Author notes that TDR rods may have helped cool the nearby soil as much as 5°C.

12. Davis, J.L., and A.P. Annan, "Electromagnetic Detection of Soil Moisture: Progress Report I," Canadian J. of Remote Sensing, V. 3. No. 1, pp. 76-86, Dec 1977.

Descriptors: Clay / Dielectric Constant / Freezing / Ground Water / Laboratory Tests / Sand / Soil Moisture Content / Soil Tests / Temperature / Time-Domain Reflectometry (TDR).

Using TDR at 10^6 to 10^9 Hz to correlate apparent dielectric constant and moisture.

$$k_a = (3.34 \pm 1.05) \exp (4.56 = \pm 0.21) m$$

Notes temperature effect for water 1.5°C yields $k_a = 87$ and 35°C yields $k_a = 75$, below 0°C k_a drops. Imaginary portions of dielectric constant ignored.

13. Davis, J.L., and W.J. Chudobiak, "In-Situ Meter for Measuring Relative Permittivity of Soils," Paper 75-1A Geol. Surv. Can., Ottawa, pp. 75-79, 1975.

Descriptors: Dielectric Constant / Ground Water / Permittivity / Soil Moisture / Soil Tests / Temperature / Time-Domain Reflectometry (TDR).

This paper describes wideband TDR used as a tool for measuring soil moisture content in-situ. A balanced parallel transmission line comprised of two rods augered into the soil was used. Depth marks were required as the speed of light in soil varies. Depths to one meter were investigated.

14. Day, M.E., Brine Disposal Pond Manual, U.S. Department of the Interior, Office of Saline Water, Report #OSW R&D No. 588, August 1970.

Descriptors: Brine Disposal / Waste Disposal / Specifications / Construction Techniques / Seepage Monitoring / Disposal Ponds.

This manual covers the design and construction of disposal ponds for use in disposing of waste brine from inland desalting plants. Specific design criteria are presented for a hypothetical brine disposal system. The manual presents data on various linings considered suitable for ponds and gives construction information for lining installation. Liner types discussed include earth linings, flexible membrane linings, hard-surface lining and soil sealants. Represents the state-of-the-art in disposal pond construction a decade ago and provides information necessary to construct monitoring programs for ponds built during this period.

15. Everett, L.G., and E.W. Hoylman, Ground Water Quality Monitoring of Western Coal Strip Mining: Preliminary Designs for Active Mine Sources of Pollution, General Electric Co., Center for Advanced Studies, Report No. EPA-600/7-80-110, June 1980.

Descriptors: Ground Water / Water Quality / Guidelines / Monitoring / Methodology / Mine Wastes / Solid Wastes.

Three potential pollution source categories have been identified for western coal strip mines. These sources include mine stockpiles, mine waters, and miscellaneous active mine sources. TEMPO's stepwise monitoring methodology (Todd et al., 1976) is used to develop ground water quality monitoring designs for each source category. These designs include description of monitoring needs, alternative monitoring approaches, and preliminary recommendations. Generic and example case studies are presented for stockpile and mine water sources. General case considerations are given for miscellaneous sources. Unit costs estimates for the monitoring designs, based on preliminary recommendations, are given.

16. Fink, Jr., W.B., and D.B. Aulenbach, "Protracted Recharge of Treated Sewage into Sand: Part II - Tracing the Flow of Contaminated Ground Water with a Resistivity Survey," Ground Water, V. 12. No. 4, July-August 1974.

EPA Form 2350-4 (4-80)

TYPING GUIDE SHEET

Descriptors: Resistivity Techniques / Ground Water / Ground Water Contamination / Flow / Flow Direction / Contamination Plume / Horizontal Profiling / Wenner Array / Effluent / Sewage Treatment.

Resistivity studies, using a standard Wenner array, were conducted in the soil (sand) in the vicinity of recharge beds of a sewage treatment plant near Lake George, New York. The purpose of the studies was to aid in determining the direction of ground water flow after the effluent from the treatment plant was discharged onto natural delta sand beds. The path of the recharged sewage effluent, as identified by lower resistivity readings, appeared to flow in a northerly direction from the sewage treatment plant along a roadway leading to a brook. Because of interference from cultural noise the authors were not able to determine whether the contaminated ground water flowed into or under the brook.

17. Fountain, L.S., SouthWest Research Institute,"Subsurface Cavity Detection: Field Evaluation of Radar, Gravity and Earth Resistitivity Methods," Proceedings of the 27th Annual Highway Geology Symposium, May 1976.

Descriptors: Gravity / Ground Penetrating Radar (GPR) / Resistivity / Subsurface / Cavity Detection / Pole-Dipole / Subsidence.

Gravity, ground-penetrating radar, and earth resistivity profiling were experimentally evaluated and compared as subsurface cavity detection methods. Tests were conducted in three different geological environments.

Verification tests showed that gravity measurements located large cavernous areas, but did not detect mud-filled troughs; radar detected air-filled cavities at maximum depths of 4.6 m (15 ft) at one site, only penetrated 3 m (10 ft) with inconclusive results at a second site, and could not resolve 0.6 m (2 ft) diameter vertical cylindrical cavities at another. Earth resistivity measurements using a pole-dipole electrode arrangement located cavities at all sites, indicating targets at depths of 24.4 m (80 ft). Both air-filled cavities, including vertical cylinders, and mud-filled troughs were detected using the resistivity technique giving accurate depth and size resolution. A large mud-filled trough was detected at a 9.1 m (30 ft) depth that extended below 30.5 m (100 ft).

The earth resistivity technique was judged to be the most successful and practical underground cavity detection method in the environments tested. It was also found to be capable of delineating the irregularities of the bedrock at the soil-rock interface.

18. Fungaroli, A.A., and R.L. Steiner, Investigation of Sanitary Landfill Behavior, U.S. Environmental Protection Agency Report #EPA-600/2-79-053a, 1979.

Descriptors: Ground Water / Leachate / Contaminants / Sanitary Landfills / Solid Waste.

This six-year study included investigation of leachate migration, the relationship between contaminant concentration and leachate volume, field capacities for various sizes of milled refuse, influence of density and depth on leachate pollutant concentrations, and the relationship of leachate chemical components to each other and to leachate volume.

The authors conclude that the refuse, source (a), and channeling, source (b), are responsible for leachate collected from a landfill during the early time period when the landfill has been placed at a relatively low initial moisture content. Once the system reaches field capacity, leachate contributed by these sources are primarily due to the advanced wetting front, source (c). Finally, when the system reaches field capacity, leachate production is due to movement of the main wetting front, source (d).

Volume II contains supplemental studies on stabilization and leachate behavior, including results from an additional year of ground water monitoring at the field site.

19. Gerhardt, R.A., Leachate Attenuation in the Unsaturated Zone Beneath Three Sanitary Landfills in Wisconsin, University of Wisconsin-Extension, Wisconsin Department of Natural Resources, Information Circular No. 35, 1977.

Descriptors: Ground Water / Sanitary Landfills / Leachate / Leaching / Suction Lysimeter / Monitoring Leachate Attenuation / Unsaturated Zone.

A study of the attenuation of leachate in the unsaturated zone beneath several landfills in Wisconsin. Changes in leachate concentration with depth and time within the unsaturated earth materials beneath the landfill sites were studied. Secondary objectives of the study included obtaining as much relevant information as possible concerning local hydrogeologic environments, as a framework for the interpretation of the changes in leachate concentrations within the unsaturated zone and determination of the impact of leachate migration and attenuation upon local ground water quality. Both conventional observation-monitoring well networks, and pressure vacuum lysimeter networks were used for data collection. Suction lysimeters placed within the unsaturated zone were shown to provide accurate data on leachate attenuation well before ground water quality was affected. The problem and drawbacks in the use of pressure-vacuum lysimeters are discussed and the several possible lysimeter configurations are given.

The authors conclude that the capacity of the unsaturated zone to attenuate leachate depends upon a variety of factors that vary greatly from one environment to another.

TYPING GUIDE SHEET

20. Glaccum, R., R. Benson, and M. Noel, "Improving Accuracy and Cost-Effectiveness of Hazardous Waste Site Investigations With a New Generation of Geophysical Methods," Ground Water Technology Division Education Session, Kansas City, Sept. 15-17, 1981.

Descriptors: Hazardous Waste Sites / Hydrogeology / Leachate / Leachate Plumes / Equipment / Ground Water Site Assessment / Geophysical Techniques / Electromagnetic Techniques / Ground Penetrating Radar (GPR) / Ground Water Monitoring / Resistivity Techniques.

This paper discusses combining geophysical techniques, including electromagnetic techniques (EM) and ground penetrating radar, with conventional ground water monitoring techniques to improve both the accuracy and cost-effectiveness of hazardous waste site investigations. EM techniques were applied to a hazardous waste site over a four-year period to determine the extent and growth of a leachate plume and to more accurately locate optimum placement of waste monitoring wells. In addition to locating the extent and flow direction of the plume itself, numerous point-sources of contamination in the layers well above the plume itself were located. EM techniques were also applied to a surface spill site to track the progress of the hazardous material as it entered a shallow ground water system. GPR was used in conjunction with EM techniques in this instance to ascertain natural subsurface conditions. Authors also discuss use of combined EM and GPR techniques to assess contaminant entry and flow in shallow karst systems.

This paper represents the first reported instance of detection of point sources of leaks uncovered in the course of this literature review.

21. Greenhouse, J.P., and R.D. Harris, "Hydrogeological Studies of a Sandy Aquifer at an Abandoned Landfill, Part 8. DC, VLF, and Inductive Resistivity Surveys," Department of Earth Sciences, University of Waterloo, Waterloo, Ontario, July 1980.

Descriptors: Surface / Geophysical Techniques / D.C. Resistivity / Very Low Frequency (VLF) / Inductive Resistivity / Leak Detection / Seepage / Landfill Contamination / Ground Water.

Direct Current (d.c.), very low frequency (VLF) and inductive resistivity surveys were conducted at the abandoned landfill at CFB Borden (near Toronto). These surveys were undertaken to assist in mapping the migration of contaminants, and continued to assess the relative usefulness of the three techniques for the task.

All three techniques were successful in outlining the regions of highest landfill-derived dissolved constituents in the sand aquifer, but the electromagnetic methods had a significant advantage over d.c. resistivity in both resolution and cost. The authors note that this

TYPING GUIDE SHEET

finding is very site-specific and emphasize the importance of evaluating geophysical methods through preliminary modeling before undertaking field work at a new site.

The authors conclude that surface resistivity surveys are successful in mapping concentrated contamination patterns, but was unreliable in less concentrated areas because of the interference of natural scatter. This lithological and topographical "noise" can easily mask the detail of a contaminant pattern and is generally inseparable from contaminant-related variations. The authors contend that if geophysical monitoring is to be useful, it is essential that resistivity surveys be undertaken as part of the pre-landfill hydrogeological studies in order to separate the natural scatter from post-landfill surveys.

22. Hackbarth, D.A., "Field Study of Subsurface Spent Sulfite Liquor Movement Using Earth Resistivity Measurements," Ground Water, V. 9, pp 11-16, 1971.

Descriptors: Resistivity Techniques / Wenner Array / Waste Disposal / Land Disposal / Ground Water Contamination / Monitoring Wells / Water Conductivity.

Spent sulfite liquor discharged into the subsurface in a seepage pit was traced by examining a grid of earth resistivity measurements made before and after dumping had taken place. The survey provided results which correlated with specific conductivity of water samples from piezometers. In addition, it proved possible to monitor the spread of the horizontal spent sulfite liquor over a 30-day period.

23. Haines, Brent M., "The Detection of Water Leakage From Dams Using Streaming Potential," SPWLA 19th Annual Logging Symposium, 1978.

Descriptors: Streaming Potentials (SP) / Leak Detection / Resistivity / SP Logging / Surface SP Surveys / Field Equipment / Reservoirs / Telluric Field / Field Technique.

Theoretical review and pragmatic example of successful application of SP techniques in the field to detect leaks from a reservoir. An initial series of surveys was conducted over Gold Creek Reservoir, one of the water supply storage units for the City of Brisbane, Australia. The dam had been exhibiting leakage through the wall for several years. Field data were collected at different times of the year to evaluate the effect of variances in water table on streaming potentials, and to allow comparison between several different data sets. Leakage zones appeared as SP troughs bounded by small positive peaks when high water level data were compared with lower water level area. Thus zones of leakage became more negative as water levels increased.

The author concludes that, quantitatively, the magnitude of streaming potential may be related to various properties of fluid and rock matrix, and to the velocity of the fluid. Field data collected indicated that there is an SP effect which correlates readily with known leakage zones. Discusses field instrumentation and equipment survey techniques, and data presentation.

24. Handy, D.L., An Earth Resistivity Survey to Observe Contaminant Migration from the Woolrich Township Landfill Site, Department of Earth Sciences, University of Waterloo, Ont., Canada, 1977.

Descriptors: Surface Resistivity / Ground Water / VLF Inductive Resistivity / Contamination Hydrogeology / Field Techniques / Instrumentation Data Presentation / Leak Detection.

An earth resistivity survey was conducted over a sanitary landfill site and the surrounding area to determine the presence and lateral extent of any ground water contamination moving from the site. The landfill received dominantly household garbage and had been operated for about six years. The survey consisted of about 200 VLF resistivity measurements covering the landfill site as well as the surrounding fields. The instrument used for the survey was a Geonics EM16R (very low frequency-VLF) portable earth resistivity meter. It is a small and convenient instrument that one man can operate easily and quickly. Its versatility is obvious when compared to conventional resistivity equipment involving a three or four-man crew plus the necessary hardware. Used in conjunction with a limited number of conventional soundings, this instrument was found to be quite suitable for this type of study and, in this case, was apparently successful in delineating a leachate plume migrating from the landfill site.

25. Haxo, Jr. H.E., R.S. Haxo, and R.M. White, Liner/ Materials Exposed to Hazardous and Toxic Sludges - First Interim Report, EPA-600/2-77-081, 61 pp., June 1977.

Descriptors: Admixes / Asphalt / Butyl Rubber / Chlorinated Polyethylene / Chlorosulphonated Polyethylene / Clay / Clay Liners / Elasticized Polyolefins / Electrolytes / Ethylene Propylene Rubber / Laboratory Tests / Leachate / Liner Pretests / Liner Permeability / Liner Strength / Liner Swelling / Liners / Liners, Soil / Neoprene / Permeability / pH / Polyvinyl Chloride (PVC) / Rubbers / Seams / Thermoplastic Elastomers / Thermoplastics / Wastes / Weathering.

Research into effectiveness and durability of the lining materials: soil, modified bentonite, soil cement, hydraulic asphalt concrete, asphalt membrane, polyvinyl chloride, chlorinated polyethylene, chlorosulfonated polyethylene, ethylene propylene rubber, neoprene, butyl rubber, elasticized polyolefine and a thermoplastic elastomer. These materials were exposed to strong acid, strong base, oil refinery bottom waste, gasoline lead wastes, saturated and unsaturated hydrocarbon oil wastes, and a pesticide. Most significant results: clays hold acids and bases only a short time; oil refinery

TYPING GUIDE SHEET

wastes tended to swell and dissolve membranes; butyl rubber and ethylene propylene rubber cannot tolerate hydrocarbons; PVC's cannot tolerate heat, sunlight or wind. The specific effects of each waste on each liner is given. Also results are given of weathering tests.

26. Haxo, H.E., "Interactions of Selected Lining Materials with Various Hazardous Wastes - II," Disposal of Hazardous Waste Proceedings of the 6th Annual Research Symposium Held at Chicago, IL, March 17-20, 1980.

Descriptors: Hazardous Wastes / Liner Material / Leachates / Seepage / Monitoring Programs.

Result of a study undertaken to assess experimentally a broad range of available lining materials including native soil, two treated bentonite clays, soil cement, hydraulic asphaltic concrete, asphaltic membrane, and a wide range of commercial flexible polymeric membranes. The various liner materials were exposed to typical hazardous wastes for periods of up to three years. Author concludes that there does not appear to be any single lining material now commercially available that is suitable for long-term impoundment of all waste. This suggests the need for compatibility studies prior to selection of liners for handling specific wastes. Tests also indicated that there is no leveling off of effects on liners with exposures to leachates over time, which suggests a need for comprehensive monitoring techniques to ensure leachate content and liner integrity.

Information reported herein on liner performance, seepage occurrences, and leachate contents provides important background information necessary to effective configuration of innovative leak detection techniques.

27. Hayward Baker Co., EarthTech Research Corp. and ENSCO Inc, "Chemical Soil Grouting Improved Design and Control," Final Report to Federal Highway Administration, McLean, VA, Contract No. DOT-FH-11-9397, Dec. 1980.

This report summarizes current knowledge in design and control techniques for chemical grouting in soils, which involves injection of a chemical agent to bring about specific changes in subsurface soil properties, either to strengthen the soil or reduce the flow of water. Although chemical grouting has been used in Europe for nearly a century, the practice has only recently been widely used in the United States for construction of urban mass transit systems. This report is directed to the civil engineering community to assist in the selection of grouting techniques by presenting evaluation and control methods.

28. Holland, W.F., K.A. Wilde, J.L. Parr, P.S. Lowell, R.F. Pohler, Environmental Effects of Trace Elements from Ponded Ash and Scrubber Sludge, Electric Power Research Institute, Palo Alto, CA, NTIS #PB-252090, 1975.

TYPING GUIDE SHEET

Descriptors: Sludge / Ash Disposal / Trace Elements / Leachate / Holding Ponds / Attenuation / Fluid Flow / Soils.

The disposal of solid wastes from coal-fired electric generating stations was investigated from the standpoint of trace element contamination of ground waters. Actual samples of ash and sludge from five operational generating stations were exposed to leaching conditions to simulate ponding. A series of batch and column tests using ash and sludge leachate in contact with natural soils was used to determine the degree of removal of trace elements in pond subsoil. Passage of pond effluent through soil was found to provide significant protection against ground water contamination by trace elements.

In addition, a discussion outlining the considerations used to quantify infiltration of waste water from a holding pond is given. Particular emphasis is placed on determination of the dependence of the infiltration rate of soil properties and tank dimensions. This information may be valuable in determining operational parameters for waste emission monitoring of seepage thorough various soils.

29. Horton, K.A., R.M. Morey, L. Isaacson, R. H. Beers, "The Complementary Nature of Geophysical Techniques for Mapping Chemical Waste Disposal Sites: Impulse Radar and Resistivity," Geo-Centers, Inc., Proceedings Conference on Control of Hazardous Materials Spills, Washington, DC, Oct. 28-30, 1981.

Descriptors: Electrical Resistivity / Impulse Radar / Hazardous Waste Sites / Site Assessment Equipment / Borehole / Ground Penetrating Radar.

A chemical waste disposal site was mapped using two different geophysical profiling techniques; impulse radar and resistivity. This paper discusses how these two geophysical techniques yield complementary information when used together with ground-truth information.

Correlation was found when resistivity profiles were overlain on corresponding impulse radar profiles. The radar signatures arising from stratigraphic units such as clays, gravels and slags could be identified with appropriate apparent resistivity values. Thus, impulse radar was used to give geologic meaning to the apparent resistivity values. Examples of this correlation are given.

The measured resistivity values for a variety of soil compositions were used in the radar equation to predict attenuation and depth of penetration of the impulse radar as a function of frequency. The predicted depth of penetration was compared with the values measured from the radar profiles obtained at the chemical waste site. Examples from a number of different burial sites were cited.

EPA Form 2350-4 (4-80)
TYPING GUIDE SHEET

30. Hughes, G.M. and K. Cartwright, "Scientific and Administrative Criteria for Shallow Waste Disposal," Civil Engineering, ASCE, V. 42, No. 3, pp. 70-73, March 1972.

Descriptors: Disposal Sites / Dilution / Dispersion / Ground Water Quality / Hydrology / Ion Concentration / Ion Exchange / Landfills / Leachate / Microbes / Percolation / Permeability / Seepage / Wastes.

Brief discussion of ground water hydrology in terms of shallow waste disposal. Postulates that present disposal criteria based on arbitrary distances (above phreatic surface, from water use point, etc.) are not based on sound hydrologic principles, and should be replaced by individual hydrologic analysis for each site.

31. Johnson, T.M, and K. Cartwright, "Implications of Solid-Waste Disposal in the Unsaturated Zone," Illinois State Geological Survey, Urbana, IL, 1978.

Descriptors: Solid Waste Disposal / Leachate / Water Table / Ground Water / Protection Methods / Monitoring Techniques / Unsaturated Zone / Suction Lysimeters / Installation Techniques / Hydrogeology.

A project was undertaken to investigate the movement and quality of leachate in the unsaturated zone beneath landfills in Illinois and to evaluate methods of monitoring soil-moisture and ground water conditions.

Three landfills representing different geologic environments and disposal practices were studied. Contaminant migration was monitored by means of observation wells and soil-water samplers and by chemical analysis of soil samples. The chemical analysis of soil-moisture samples collected beneath and adjacent to the landfills provided valuable information on the extent of contamination from leachate. Migration of pollutants through the unsaturated zone was detected at each site even though monitoring wells appeared to be virtually unaffected.

The implications of waste disposal in unsaturated materials extend to the use of gravel drains and landfill liners for collecting or containing leachate. Although collection systems may function well under saturated conditions, they may be less effective under conditions of partial saturation.

32. Johnson, R.W., R. Glaccum, and R. Wojtasinski, "Application of Ground Penetrating Radar to Soil Survey," Soil and Crop Science Society of Florida Proceedings, V. 39, Oct. 1979.

TYPING GUIDE SHEET

Descriptors: Geophysical Methods / Ground Penetrating Radar / Soil Remote Sensing / Site Assessments / Instrumentation / Data Presentation / Data Interpretation.

This report discusses the theory and application of ground penetrating radar (GPR) as a soil survey tool. GPR was tested at two locations in central Florida. Both sites had order 2 soil surveys, with several contrasting soils. Approximately 8 km of transects were run with the GPR. The results of the GPR survey were confirmed by borings at intervals of 30 m along the lines of transects, and data from both sources were compared with the soil maps. The GPR data generally proved accurate in measuring the depth to, and thickness of, several kinds of soil horizons. Data was of generally high clarity. Generally, the GPR record substantiated many delineations on the soil map, whereas in some places it showed where more precise boundaries could be placed. However, GPR could not record all the subtle changes noted in the soil boring logs, such as a slight increase or decrease in texture as from sandy loam to sandy clay loam.

33. Kays, W.B., Construction of Lining for Reservoirs, Tanks, and Pollution Control Facilities, John Wiley & Sons, New York, 379 p., 1977.

Descriptors: Reservoirs / Liners / Failure Mechanisms / Pollution Control Linings / Reservoir Tables.

This book is concerned with the technology of building storage facilities to contain waste materials. The author examines hydraulic linings from a broad overview of design and utilization. The author attempts to list the various rigid and flexible lining materials, their costs and their advantages and disadvantages. A chapter is devoted to failure mechanisms and appendices list design information, trade names, sources and a set of 93 reservoir tables on the volumes and lining areas of circular, square and rectangular tanks and reservoirs.

34. Kean, W.F., R.B. Rogers, "Monitoring Leachate in Ground Water by Corrected Resistivity Methods," Bulletin of the Assn of Engineering Geologists, V. XVIII, No. 1, pp. 101-107, 1981.

Descriptors: Surface / Electrical Resistivity / Fly Ash / Leachate Plume / Landfill / Leak Detection / Seepage / Field Techniques / Laboratory Studies / Ground Water Monitoring / Wenner Array / Contamination / Ground Water / Contaminated Ground Water / Aquifer.

Surface electrical resistivity methods were employed in a study monitoring the movement of fly ash leachate at a landfill site. Because the monitoring took place during the various seasons of the year, the ground water temperatures were not constant. Therefore, it was difficult to directly correlate changes in surface resistivity through time with changing ground water contamination because the temperature effect on resistivity could possibly mask the salinity (contamination) effect. Laboratory determinations were made of the

TYPING GUIDE SHEET

resistivity of samples from well borings in the study area as a function of temperature, saturation and salinity. The laboratory sample container consisted of a plastic box 4 in. by 3 in. by 2 in. The resistivity was measured using a Wenner electrode configuration with a 1 in. electrode spacing.

The results of the laboratory studies were used to adjust all of the surface resistivity measurements to a common ground water temperature. After correction, the surface resistivity measurements positively identified the direction of the leachate movement, as well as changes in the concentration of the leachate with time.

35. Kirby, P.C., "The Selection of Membrane Materials for Water Distribution and Allied Applications," Water Research Center Medmenham Laboratory, England, Technical Report TR 113, 63 p., May 1979.

Descriptors: Biogradation / Biological Activity / Bitumen Membrane / Butyl Rubber / Coupons / Extraction / Gassing / Glass Reinforced Polyester / Liners / Liner Chemistry / Liner Maintenance / Liner Pretest / Liner Permeability / Liner Strength / Liner Swelling / Liner, Membrane / Liner, Spray-on / pH / Plastics / Plastics Identification Tests / Polymer / Polyurethane / Rubber / Sealing / Seams / Temperature / Thermoplastics / Underdrains / Vegetation / Vulcanized Plastic / Wastes / Wave Erosion / Weathering / Wind Erosion / Ethylene Propylene Rubber / Chlorosulphonated Polyethylene / Polyethylene / Polyvinyl Chloride / Elasticized Polyolefin / Reverse Hydrostatic Uplift / Distress.

This report discusses engineering properties to be considered for liner selection, dealing with lined water reservoirs, floating covers, and refuse tips. The author lists membranes and tabulates chemical resistance to acid, alkali, aromatic solvents, and oils. Discusses causes of liner stress: stones, folds, settlement, wind, root and rodent penetration, and gassing. Describes seaming (thermal vs. solvent adhesive), tongue-in-groove and taped solvent. Lists materials available in U.K. with advantages, disadvantages, and cost in pounds.

36. Klefstad, G., L.V.A. Sendlin, and R.C. Palmquist, "Limitations of the Electrical Resistivity Method in Landfill Investigations," Ground Water, V. 13, No. 5, pp. 418-27, Sept.-Oct. 1975.

Descriptors: Resistivity Techniques / Leak Detection / Contamination / Landfills / Waste Disposal / Threshold Values / Leachate / Ground Water / Wenner Arrays / Ground Water Contamination.

A detailed investigation of the interrelationship between electrical resistivity, material variation, and water quality was conducted in the alluvial deposits of the Skunk River at Ames, Iowa. The lateral variation of materials at the site resulted in a large natural scatter in the resistivity response. The decrease in resistivity due to contamination was not greater than this natural scatter and thus could not be detected. These results suggest a relationship between the scatter levels at any site and the minimum degree of contamination necessary to be detected.

37. Koerner, R.M., A.E. Lord, Jr., J.J. Bowders, and W.W. Dougherty, Drexel University, "Use of CW Microwaves to Locate Voids Beneath Paved Areas," Submitted for review and possible publication, ASCE Journal of Construction Division, Jan. 15, 1981.

Descriptors: Microwave / Nondestructive Testing / Radar / Settlement / Subsidence / Testing / Void Detection / Equipment / Instrumentation.

Evaluates the use of continuous wave (CW) microwaves, which can penetrate upper paved materials, as a technique to locate voids beneath paved areas. Depending upon the nature of the underlying material (soil, air, or water) the technique gives different return reflections, and has been applied in the field for pavement applications to determine the location and extent of subsurface anomalies, such as voids and buried pipes or containers. It is concluded that the method could be used to indicate differences between underlying material (soil, air or water), but fell short of assessing the thickness of an air void when present.

38. Koerner, R.M., A.E. Lord, Jr., J.J. Bowders, J.E. Sankey, Drexel University, "Use of NDT Methods to Detect and Locate Buried Containers Verified by Ground Truth Measurements," Presented at Hazardous Materials Spills Conf., Milwaukee, WI, 1982.

Descriptors: Nondestructive Techniques (NDT) / Buried Containers / Geophysical Methods / Hazardous Wastes / Seismic Refraction / Electrical Resistivity / Ground Probing Radar / Continuous Microwave / Metal Detector / VLF Electromagnetic Techniques / Magnetometer / Excavation / "Ground Truth" / Soils / Data Interpretation / Field Technique.

The results of this on-going study is a critical assessment of the advantages and disadvantages of a number of NDT methods that are capable of ground penetration to locate various subsurface anomalies - in this case various-sized containers, both metal and non-metal. The study was designed to compare one technique to another and to follow the field tests with site excavation to determine the exact size and nature of the anomaly. Candidate technologies for the study included the following:

- Seismic refraction
- Electrical resistivity
- Ground probing radar
- Continuous microwaves
- Metal detector
- VLF electromagnetic
- Magnetometer.

Techniques are cross compared in terms of effectiveness, cost and ease of implementation. Tentative conclusions should indicate:

- A metal detector should be the first method used for exploratory work,
- If the containers are shallow, but not of steel, the very low frequency electromagnetic method is best for soils of high saturation (50%) and the continuous wave microwave method is best for dry to partially saturated (50%) soils,
- For containers buried deeper than 5 feet and in soils of high saturation (50%), the magnetometer seems best suited although individual drum definition is not particularly clear.
- For containers buried deeper than 5 feet in dry or partially saturated (50%) soils, GPR seems well suited.

The other NDT techniques used in this study and noted in the literature require much more field (and laboratory) development before they can be recommended for future field investigation. For all of them, "ground truth" experiments as conducted in this study under a wide variety of field conditions seems justified.

39. Koerner, R.M., A.E. Lord, J.E. Brugger, and J.J. Bowders, Drexel University, "Utilization and Assessment of Ground Probing Radar to Locate and Monitor Subsurface Fluid FLow," Proceedings, Management of Uncontrolled Hazardous Waste Sites Conference, Washington, DC, Oct. 1981.

Descriptors: Leak Detection / Seepage / Ground Water / Ground Probing Radar Pulsed Microwave / Data Interpretation.

This paper is directed at assessing the suitability of ground probing radar (GPR) to detect subsurface seepage flow of ground water. Three sites consisting of distinctly different soil conditions (clay, silt, and sand) were monitored for approximately one year to assess the effects of:

- Fluctuation of water table over time of day,
- Fluctuation of water table over time of year,
- Varying temperature
- Different frozen ground conditions
- Varying soil moisture above the water table.

In order to verify the actual water table location, a series of water observation wells were installed adjacent to the GPR survey line at each site location. Thus a percent accuracy, based on "ground truth" information, could easily be calculated.

The authors conclude that GPR is easy to deploy and that water surface location in coarse-grained soils is quite accurate (±10%) whereas in fine-grained soils (clay and silt) water surface location is both difficult and inaccurate (±50%).

TYPING GUIDE SHEET

40. Koerner, R.M., A.E. Lord, Jr., T.A. Okransinski, and J.S. Reif, Drexel University, "Detection of Seepage and Subsurface Flow of Liquids by Microwave Interference Methods," Proc. Conf. on Control of Hazardous Materials Spills, Miami Beach, FL, pp. 287-92, April 1978.

Descriptors: Seepage / Subsurface Flow / Ground Water / Nondestructive Testing (NDT) / Microwave Interference Methods / Electromagnetic Spectrum Leak Detection / Field Procedures / Equipment.

This paper reports the results of a laboratory and field study to determine the validity and accuracy of using the microwave interference method to detect subsurface water. The study indicated that, by transmitting microwaves continuously, alternating constructive and destructive interference patterns will be received in the presence of two separate distinct interfaces. These patterns can be analyzed either manually or digitally to give the depth to the reflective interface. The error of the calculated depth to the actual depth was within 10% for both laboratory and field tests using a buried steel plate. The error was somewhat greater for the depth to a water surface due to its less distinct interface. Although the method was still in the research stage, the authors felt that preliminary results demonstrated that the technique was capable of penetrating great depths with additional power, was reasonably reliable as a predictive method, economically competitive, and easy to apply and interpret.

41. Koerner, R.M., W.M. McCabe, L.F. Baldivieso, "Acoustic Emission Monitoring of Seepage," J. of the Geotechnical Engineering Div, Proc. of ASCE, V. 107, No. GT4, April 1981.

Descriptors: Acoustic Emissions / Monitoring / Seepage / Soil Stability / Instrumentation / Field Technique / Leak Detection / Borehole.

This technical note illustrates the technical feasibility of acoustic-emissions (AE) methods, and quantifies certain aspects of AE monitoring of seepage of water through soil. The work described is a laboratory study in which both clear water and turbid water were passed through a column of soil at various flow velocities. Flow rates and AE rates from these laboratory studies were then compared to a previously-conducted field study at the site of leakage beneath a small earthen dam, where the method was applied successfully, downhole, to locate seepage along the axis of the dam.

42. Koerner, R.M., W.M. McCabe, and A.E. Lord, Jr., Drexel University, State-of-the-Art Lecture: Acoustic Emission Behavior and Monitoring in Soils, AST Symposium on "Acoustic Emission in Geotechnical Engineering Practice," Detroit, MI, June 1981.

Descriptors: Acoustic Emission (AE) / CLay / Deformation Monitoring / Equipment / Field Techniques / In-situ Testing Instrumentation / Laboratory Testing / Microseisms / Microseismic Activity / Monitoring / Non-Destructive Evaluation / Slope Stability / Stress Wave Emissions.

This state-of-the-art paper on acoustic-emission (AE) activity in soils presents the basic fundamentals of AE technique as demonstrated in small and large-scale laboratory tests, and in field situations. Specific case histories are given for slope stability monitoring of dams and embankments, soil movements from horizontal and vertical deformations, monitoring of hydrofracturing in cement and chemical grouting, and seepage monitorings beneath a small earth dam. In addition, detailed discussion of instrumentation and system configuration, along with descriptions of field techniques are given.

The authors conclude that the current qualitative status of this technique (i.e., no AE indicates stability; low emissions indicate small movements; high emissions indicate instability) should move to a quantitative status. Eventually it may be possible to identify AE signatures of different soils, leading to a quick and accurate assessment of actual soil stress or seepage levels in any given situation. Field demonstrations of actual seepage detection from boreholes through an earth dam have particular application to the possible use of AE techniques to detect leakage from landfill sites.

43. Konikow, L.F., "Modeling Chloride Movement in the Alluvial Aquifer at the Rocky Mountain Arsenal, Colorado," U.S. Department of the Interior, Geological Survey, USGS Water Supply - Paper 2044, GPO Stock No. 024-001-02963-4, 1977.

Descriptors: Mathematic Models-Water / Aquifers / Chlorides / Colorado / Water Resources Management / Flow Measurement / Hydrology.

The impact of waste disposal on U.S. water resources through a solute-transport model applied to the problem of ground water contamination at the Rocky Mountain Arsenal near Denver is detailed. The computer model, which coupled a finite-difference solution to a ground water flow equation with the method-of-characteristics solution to the solute-transport equation determined the effects of several factors that controlled changes in chloride concentrations, and it successfully reproduced the record of chloride contamination observed during 30 years. The simulation model, a description of the study area, and the model's application are explored. The model is generally applicable to a wide variety of ground water contamination problems.

44. Kurzeme, M., "In-Situ Investigations Using SH-Waves," J. of the Soil Mechanics and Foundations Division, Proc. of the American Society of Civil Engineers, pp. 341-56, Feb. 1971.

Descriptors: Nondestructive Testing (NDT) / Shear Waves / In-Situ Testing / Soils / Data Interpretation / Instrumentation / Equipment.

This article describes work conducted under sponsorship of the Institute of Highway and Traffic Research, University of New South Wales, showing that it is possible to generate horizontally polarized shear waves (SH waves) at the surface of layered road pavements and soil structures, and to observe the resulting velocity dispersion with frequency. The interpretation of the observed dispersion results is dependent on the extent the real structure departs from the idealized material and structural model. Possible application of the technique to saturated soils is not discussed. Author discusses field technique, data interpretation and equipment usage.

45. Lewis, R.W., and C. Humpheson, "Numerical Analysis of Electro-Osmotic Flow in Soils," J. of the Soil Mechanics and Foundations Division, Proc. of the American Society of Civil Engineers, V. 99, No. SM8, August 1973.

Descriptors: Electro-osmosis / Saturated Soils / Phreatic Surface.

A method for analysis of phreatic surface problems with respect to hydrodynamic and electrokinetic forces shows that consolidating soil decreases porosity, thus increasing soil density and decreasing hydraulic permeability. Since water flows from anodes toward cathodes, soil will dry around the anodes. This causes an increase in resistivity and a decrease in electrical conductivity. In zones where electrochemical hardening occurs, there will also be a decrease in flow and increase in resistivity. Electro-osmotic permeability is also known to be time-dependent and the capacitance of the soil is a function of moisture content.

46. Lewis, J.O., and D.A. Duncan, "Evaluation of the Impact of Landfill Leachate on Ground Water Quality at the Lexington County, South Carolina Site," South Carolina State Dept. of Health and Environmental Control, Report No. EPA-904/9-80-050, April 1980.

Descriptors: Ground Water / Water Pollution / Monitoring / Leachate / Hydrogeology / Water Wells / Aquifers / Percolation.

The report describes efforts made to monitor the leachate impact on the ground water at the Lexington County, South Carolina, landfill. The geology and hydrogeology of the region, as well as the landfill in particular, are discussed in detail to help determine the movement of ground water near the landfill. The purpose of the report was to isolate the ground water effects of a nearby abandoned site, Cayce Dump. Fourteen stratigraphic test holes, six monitoring wells, and three existing wells were used for ground water monitoring.

47. Lofy, R.S., H-T. Phung, R.P. Stearns, and J.J. Walsh, Subsurface Disposal of Municipal Wastewater Treatment Sludge, U.S. Environmental Protection Agency, Office of Solid Wastes, Report No. EPA-530-SW-167-C, 1978.

Descriptors: Sludge Disposal / Ground Water Contamination / Ground Water Monitoring / Leachate / Sludge / Geological Surveys Attenuation Mechanisms.

An assessment of ground water quality in the vicinity of eight landfill sites accepting various quantities of municipal sewage sludge was performed. An appraisal was also made of the operations and economics at each location. The study included a preliminary assessment of the environmental impacts of sewage sludge burial practices at the eight sites. Additional data on leachate and ground water quality trends over a 12-month period were obtained. Two sites were selected for more intensive ground water monitoring to determine the areal extent and degree of ground water quality impact. The results showed that landfilling of sewage sludge released significant contaminants in the form of leachate. Contaminants traveled at least several hundred meters beyond the immediate disposal area, despite the existence of soil strata with low permeability. The monitoring data demonstrated the extreme difficulty in selecting monitoring well locations and sampling depths and establishing a sampling frequency necessary to obtain valid information for measuring landfill impacts on ground water.

48. Lord, Jr., A.E., S. Cohen, and R.M. Koerner, "Use of Penetrating Radiation as a Potential NDT Method Applied to Hazardous Material Spill Problems," Drexel University Progress Report #3 to U.S. Environmental Protection Agency, Industrial/Environmental Research Laboratory, OHMSB, Cooperative Agreement No. CR807777010, January 1981.

Descriptors: Penetrating Radar / Stress Analysis / High Speed Radiography / Activation Analysis / Container Evaluation / Hazardous Materials / Equipment / Manufacturers / Nondestructive Testing (NDT).

This report is one of a series of progress reports prepared by Drexel University under cooperative agreement with the U.S. Environmental Protection Agency, OHMSB, to investigate non-destructive testing methods to locate buried waste drums and evaluate hazardous materials spills. This particular report discusses the theory and application of penetrating radar to the problems under study. Current industrial applications of this method include:

- Investigating contents of sealed containers,
- Locating defects in homogeneous materials,
- Stress analysis,
- High speed radiography,
- Activation analysis.

The report gives information on equipment and manufacturers and discussed actual field application of the technique.

The authors conclude that, although this technique has found wide industrial applications, its applicability to evaluation of storage containers in waste disposal sites is limited due to technical limitations. These include the need for both front and rear of a specimen to be accessible to produce a radiograph and the subtle, and sometimes ambiguous, data results that require highly skilled interpretation. In addition, radiation safety procedures must be strictly adhered to in order to prevent injury.

49. Lord, Jr. A.E., S. Cohen, and R.M. Koerner, "Use of Electrical Potential Measurements as a Possible NDT Method Applied to Hazardous Material Spill Problems," Drexel University Progress Report No. 7 to U.S. Environmental Protection Agency Industrial/Environmental Research Laboratory OHMSB, July 1981.

Descriptors: Streaming Potential / Self-Potential / Fluid Flow / Earth Current / Seepage / Dams / Reservoirs / Leak Detection / Electrical / Potentials / Instrumentation / Data Interpretation.

This progress report to the U.S. Environmental Protection Agency was prepared under a cooperative agreement with Drexel University, to investigate non-destructive testing methods to locate buried waste drums and evaluate hazardous materials spills. Discussed herein is the possible application of electrical potential measurements to these problems. Earth potential phenomena which can lead to passive sensing methods to detect underground anomalies are discussed in terms of global and local effects and streaming potential. Streaming potentials occur when an ionic solution (e.g. ground water, leachate) is forced at some hydrostatic pressure through the voids of rock or soil, creating a potential difference. Also discussed are field measurement techniques used to detect electrical potentials, and current applications of the technique in the field, which include detection of leaks through dams and reservoirs, liquid seepage from metal pipes and precious metal prospecting. A brief discussion of data presentation is also given, along with a list of equipment manufacturers. The authors conclude that these techniques have limited application to location of buried waste drums or evaluation of hazardous materials spills because of the weak signal and difficulties in distinguishing signals from noise.

50. Lord, A.E., S. Tyagi, and R.M. Koerner, "Use of Very Low Frequency Electromagnetic (VLF-EM) Measurements as a Possible NDT Method Applied to Hazardous Material Spill Problems," Drexel University Progress Report No. 8, Cooperative Agreement No. CR807777010, U.S. Environmental Protection Agency, OHMSB, July 1981.

Descriptors: Hazardous Waste / Spills / Very Low Frequency (VLF) Techniques / Electromagnetic (EM) Techniques / Leaks / Leak Detection / Instrumentation Eddy Current / Prospecting / Field Technique / Leachate Plume.

This Progress Report No. 8 to the U.S. Environmental Protection Agency was prepared under a cooperative agreement with Drexel University to investigate non-destructive testing methods to locate buried waste drums and evaluate hazardous materials spills. This report discusses the application of very low frequency electromagnetic (VLF-EM) measurements to the problems under study. Referred to by the authors as eddy-current techniques, they also distinguish VLF-EM techniques from VLF techniques employing very low frequency signals transmitted for the purpose of military communications. This technique has been used successfully to detect various subsurface anomalies, including permafrost detection, ground water exploration, mineral exploration, landfill impoundments, and hazardous materials spills. Case histories of successful application of this technique to mapping leachate migration are cited. Both theoretical and practical aspects of the technique are discussed, along with system configuration and field application parameters.

51. Lord, Jr., A.E., R.M. Koerner, and F.J. Freestone, Drexel University, "The Identification and Location of Buried Containers Via Nondestructive Testing Methods," unpublished paper, 1981.

Descriptors: Nondestructive Testing (NDT) / Buried Containers / Ground Probing Radar / Metal Detector / Magnetometer / Electrical Resistivity / VLF Electromagnetic / Seismic Refraction / Sonar (Pulse ECHO) Acoustics / Infrared Radiometry / Nuclear Method / Continuous Wave Microwaves / Equipment Costs / Data Interpretation / Seepage / Leak Detection.

This paper presents a review of various nondestructive testing methods to locate buried containers or drums. Seven NDT methods were reviewed: ground probing radar, metal detectors, VLF electromagnetic, sonar, infrared, nuclear, and continuous wave microwave. Each method is discussed in terms of theory and application. Case histories are given and comparisons between techniques, in terms of cost and efficacy, are made. The authors conclude that metal detectors represent the technique of choice for buried drum location at shallow depths. At greater depths magnetometers are recommended, followed by ground probing radar, which gives excellent resolution but is costly and requires expertise to apply.

52. Lytle, R.J., "Measurement of Earth Medium Electrical Characteristics: Techniques, Results, and Applications," IEEE Trans. Geosci. Electron GE-12 (3), pp. 81-101, 1974.

Descriptors: Geotomography / Electromagnetic Techniques / In-situ Measurements / Borehole Measurements / Laboratory Tests / Wave Tilt Methods / Surface-to-Hole Methods / Dielectric Constant / Soils / Rock.

A brief review of electrical and electromagnetic measurement techniques, results and factors influencing the electrical properties of geologic materials is given. Some practical applications of the techniques are offered. A good list of references is also given.

Techniques discussed:

Laboratory Measurements

Methods: Transmission line, resonant cavity, waveguide, scattering and transmission.

In-Situ Surface Measurements

Methods: Four-probe resistivity, mutual inductance, wave tilt, reflection coefficient, multiple path interference, intensity versus range.

In-Situ Drill Hole Measurements

Methods: Mutual inductance, surface-to-hole transmission, antenna impact impedance, axial electric field, transmission line, hole-to-hole transmission, multiple path interference, four-probe.

Results of conductivity and dielectric constant of geologic materials are given. An example of the tomographic technique between two boreholes is discussed.

53. Lytle, R.J., and K.A. Dines, "An Impedance Camera: A System for Determining the Spatial Variation of Electrical Conductivity," Lawrence Livermore Laboratory, University of California, Report UCRL-52413, Jan. 1978.

Descriptors: Geophysical Techniques / Subsurface / Electrical Conductivity / Surface / Borehole Resolution / ELectromagnetic / Computer Simulation / Impedance Camera.

A data collection and data interpretation method is presented for predicting, from measurements made on the periphery of the core sample, the electrical conductivity distribution with core samples. This method uses an array of electrodes on the periphery to probe through the core sample. Surprisingly accurate detail can be seen in the estimated conductivity distribution. This method has been demonstrated using synthetic examples modeled and analyzed on a computer. Extensions of the procedure may be useful in subsurface geophysical probing and remote probing methods using physical phenomena satisfying Laplace's equation.

Technique is conceptually applicable to ground probing for leak detection at hazardous waste sites; potentially useful because of the clarity of data, simplicity of interpretation, and increase in detail.

54. Lytle, R.J., and K.A. Dines, "Iterative Ray Tracing Between Boreholes for Underground Image Reconstruction," IEEE Transactions in Geoscience and Remote Sensing, V. GE-18, No. 3, July 1980.

Descriptors: Geophysical Techniques / Cross Borehole / Electromagnetic / Seismic / Geometrical Optics / Subsurface / Geotomography.

A computerized method is described for calculating an image of the refractive index distribution in a plane bounded by two underground boreholes. The scanning geometry is assumed to be limited to probing from borehole to borehole, with rays at numerous depths and angles to effectively cover the cross section between holes. A geometrical optics model is assumed for the transmission data. The authors stress situations where significant bending of electromagnetic or seismic rays occur.

55. Lytle, R.J., D.L.Lager, E.F. Laine, and D.T. Davis, "Using Cross-Borehole Electromagnetic Probing to Locate a Tunnel," Lawrence Livermore Laboratory, Report UCRL-52166, 1976.

Descriptors: Subsurface / Cavity Detection / Electromagnetic Probing / Boreholes / Field Technique / Data Interpretation.

Theoretical and experimental studies of electromagnetic interaction with a tunnel found that signal minima can be used to detect and locate the tunnel. These minima are found on the transmission side of the tunnel, the side opposite the signal transmitter. No useful variation was found on the reflection side, the same side as the transmitter. From the appearance of the signal and comparison with Fresnel diffraction, the main mechanism of signal interaction with the tunnel seems to be diffraction rather than refraction or reflection. The signal is appreciably affected by tunnel shape and the presence of backfill, but not by a metal screen in the tunnel. The best results were obtained at a frequency of 57 MHz, giving a wavelength in the ambient medium about equal to the tunnel's radius. Experiments were made around a tunnel near Gold Hill, Colorado. The tunnel was horizontally and vertically located within three feet.

The data interpretation method described in this article allows for rapid interpretation of data in the field. All that is required is: successful transmission, a record of the variation of signal intensity with depth for a number of fixed source/receiver orientations, ruler, pen and graph paper.

56. Matrecon, Inc., Lining of Waste Impoundment and Disposal Facilities, Under Contract to U.S. Environmental Protection Agency, Cincinnati, OH, Report No. SW-870, Sept. 1980.

Descriptors: Hazardous Waste / Municipal Solid Waste / Leachate / Lining Materials / Lining Technology / Soils / Design Construction / Flexible Membrane Liners / Soil Liners / Asphalt Liners / Attenuation Properties Landfill, Geotextiles / Geomembranes / Ground Water / Monitoring Techniques / Leachate Collection System.

This report is a comprehensive review of factors affecting selection, performance, installation and maintenance of specific liners and cover materials for specific containment situations, based upon current state-of-the-art of liner and other pertinent technologies. Also includes descriptions and characteristics of various types of wastes and their industrial source, with reference to polluting and potentially polluting components, and to the effect of leachate on various types of low permeability man-made liners. Liner types discussed range from soils and clays, through admixed liners, flexible polymeric membranes, sprayed-on linings, soil sealants, and chemical absorptive liners. Thorough discussion of installation practices, effects of waste fluids on soils and possible failure mechanisms provide necessary parameters for selection of possible innovative techniques to detect liner failure and leachate seepage.

57. Miller, D.W., ed., Waste Disposal Effects on Ground Water, Office of Water Supply and Office of Solid Waste Management Programs, U.S. Environmental Protection Agency, 1977.

Descriptors: Ground Water / Waste Disposal / Contamination / Fluid Flow / Federal Legislation.

A comprehensive survey of the occurrence and control of ground water contamination resulting from waste disposal practices. Provides a thorough background in the subject, dealing with the full range of waste disposal practices. The limitations of current monitoring techniques, and the behavior of leachate and fluid flow pertaining to potential contamination of ground water are also discussed.

58. Mitchell, J.K., J.A. Greenberg, and P.A. Witherspoon, "Chemico-Osmotic Effects in Fine-Grained Soils," Proc. ASCE J. Soil Mech. and Found. Div., V. 99, No. SM4, pp. 307-23, April 1973.

Descriptors: Chemico-Osmotic Coupling / Clay / Clay Structure / Electrolytes / Ion-Concentration / Ion Gradient / Permeability / Pore Pressure / Salinity / Salts / Seepage Pressure / Soil Chemistry / Soil Compressibility / Soil Moisture Content.

Describes a mathematical treatment coupling ionic diffusions and pore water osmosis. The effect likely is small for most soils except very fine-grained active soils such as bentonite. Conventional consolidation falls out as a special case in the absence of chemico-osmotic coupling. Suggests application for chemico-osmotic consolidation, drawing water out and salt into soil mass.

59. Mitchell, J.K., and W.N. Houston, "Causes of Clay Sensitivity," Proc. ASCE J. of Soil Mech. and Found. Div., V. 95, No. SM3, pp. 845-71, May 1969.

Descriptors: Clay / Clay Structure / Dispersing Agents / Electrolytes / Extractics / Ion Exchange / Leaching / Permeability / Phosphorus / Salt / Salt, Cationic / Salinity / Soil Chemistry / Soil Strength / Thixotrophy / Wastes / Weathering.

Basic review of clay sensitivity. Identifies eight factors (metastable fabric, silt skeleton with clay bonds, cementation, ion exchange, salt leaching, weathering, thixotropic hardening and dispersing agents) causing sensitivity. Notes incident of phosphorus dump leachate causing quick clay conditions.

60. Ogilvy, A.A., M.A. Ayed, and V.A. Bogoslovsky, "Geophysical Studies of Water Leakages from Reservoirs," Geophysical Prospecting, V. 17, pp. 36-62, 1969.

Descriptors: Streaming Potentials (SP) / Flow Potential / Leak Detection / Reservoirs / Thermometry / Laboratory Study / Soil Types / Field Equipment / Field Technique.

This is one of the early reports from the Soviet Union of successful laboratory and field application of streaming potential to detect water leakage from dams and reservoirs. Laboratory tests indicated that laws governing SP are apparently violated under turbulent flow conditions. In addition, the technique appears to work best in sands of medium-sized grains. SP values dip abruptly with lower permeability values. When salination corresponds to specific resistivity of less than 10 ohm-cm, noticeable SP values cannot be expected. The limitation on the technique may have importance in leachate detection, depending upon content.

61. Reed, P.C., K. Cartwright, and D. Osby, "Electrical Earth Resistivity Surveys Near Brine Holding Ponds in Illinois," Illinois Inst. of Natural Resources, Environmental Geology Notes 95, April 1981.

Descriptors: Resistivity Techniques / Holding Ponds / Hydrogeology / Leachate / Leachate Migration / Unsaturated Zone / Soluble Salts / Brine / Ground Water Monitoring.

Electrical resistivity surveys were conducted in the vicinity of five oil field, brine holding ponds to develop a methodology for identifying elevated levels of soluble salts near oil fields. Four sites were selected for detailed study of a possible relationship between changes in apparent electrical earth resistivities and changes in water quality.

The resistivity surveys clearly indicated the direction and extent of salt water migration around the holding ponds. The authors conclude that apparent resistivity measurements can be used to approximate quality of the ground water because there is a direct relationship between the resistivity and water quality. This relationship can be used to indicate relative salinities; however, the relationship should be used with caution in making estimates of water salinity.

Brine migration has not affected the regional water quality, and appears to be of limited regional significance. Studies of water chemistry from observation wells at the selected holding pond sites indicated that some attenuation of the brine is occurring.

These studies were able to detect migration of wastes in the unsaturated zone prior to significant damage to the ground water, one of a very few instances reported in the literature. The high conductivity of the brine probably contributed to the relative ease of detection.

62. Rogers, R.B., W.F. Kean, "Monitoring Ground Water Contamination at a Fly Ash Disposal Site Using Surface Electrical Resistivity Methods," Ground Water, V. 18, No. 5, pp. 472-78, Sept.-Oct. 1980.

Descriptors: Electrical Resistivity / Surface / Landfill / Leachate / Leak Detection / Fly Ash / Wenner Array / Hydrogeology / Field Techniques / Laboratory Studies / Data Presentation / Data Interpretation / Electrical Profiles / Ground Water Contamination / Monitoring Wells.

Ground water quality was monitored at a fly ash disposal site. The monitoring technique consisted of electrical resistivity soundings and profiles in conjunction with analysis of water samples from 33 wells on the site. In addition, laboratory measurements were made on samples from the well borings to determine the changes in resistivity of each lithology as a function of water saturation, and the temperature and conductivity of the pore fluid.

For a line approximately perpendicular to the ground water flow, it was possible to detail the subsurface lithology using electrical sounding, and in conjunction with laboratory studies, it was possible to determine the vertical and horizontal extent of the contamination for that cross section.

Electrical profiles, which were taken on a monthly basis, monitored the changing concentration of leachate after the profiles were corrected to a common ground water temperature.

It is important to note that a thorough site investigation had been conducted prior to this survey and that this information was a key to successful conduct of the resistivity program.

63. Schmugge, T.J., T.J. Jackson, H.L. McKim, "Survey of Methods for Soil Moisture Determination," *Water Resources Research*, V. 16, No. 6, pp. 961-79, Dec. 1980.

Descriptors: Soil Moisture / Gravimetric / Nuclear / Electromagnetic / Soil Physics Models / Remote Sensing / Evapotranspiration / In-Situ Methods / Thermal Infrared / Active Microwave / Passive Microwave / Dielectric Properties.

This paper discusses methods of in-situ soil moisture determination including gravimetric, nuclear, and electromagnetic techniques, soil physics models that track the behavior of water in the soil in response to precipitation and evapotranspiration, and remote sensing approaches that use the solar, thermal, infrared, and microwave portions of the electromagnetic spectrum. The efficacy of these techniques varies from application to application. The authors thus propose a conceptual scheme for combining these approaches into an integrated system. Since the authors' interest is confined largely to agricultural applications, the techniques examined are limited largely to the soil root zone. The thickness of this layer typically ranges from 1 to 2 m.

64. Shultz, David W., M.P. Miklas, Jr., SouthWest Research Institute, "Assessment of Liner Installation Procedures," *Proceedings of the 6th Annual Research Symposium on Disposal of Hazardous Waste*, Chicago, IL, EPA Report No. EPA-600/9-80-010, NTIS Publication No. PB80-175086, pp. 135-45.

Descriptors: Landfill Liners / Installation Procedures / Quality Assurance.

This paper presents a review of current methods and equipment used to prepare supporting subgrade and place liners at various waste impoundment sites. The 15 sites reviewed included landfills, waste water impoundments, and potable water reservoirs. The discussion reports on methods and equipment used to prepare subgrade for liner placement, methods and equipment used to place liner material, problems encountered, and important characteristics that must be considered during design and construction of lined facilities. A discussion of quality assurance considerations is also included.

65. Stokoe, K.H., R.D. Woods, "In-Situ Shear Wave Velocity by Cross-Hole Method," *J. of the Soil Mechanics and Foundations Division*, Proc. of the American Society of Civil Engineers, pp. 443-60, May 1972.

Descriptors: Cross-Hole Seismics / Saturated Soils / In-situ / Non-destructive Testing (NDT) Technique / Field Procedures / Equipment / Data Interpretation.

This article explains cross-hole seismic test methods for obtaining in-situ shear wave velocity. This method can be used above or below water table and results indicate properties of material. There is some change in velocity in saturated soils, but this is not emphasized.

66. Stollar, R.L., and P. Roux, "Earth Resistivity Surveys - A Method for Defining Ground Water Contamination," Ground Water, V. 13, No. 2, March-April 1975.

Descriptors: Resistivity Techniques / Site Assessments / Ground Water / Ground Water Contamination / Leachate / Leak Detection / Wenner Array / Cultural Noise / Landfills / Ground Water Monitoring / Monitoring Wells.

Four case histories of earth resistivity surveys conducted at industrial waste disposal and landfill sites are discussed in this paper. The areas underlain by the contaminated ground water bodies ranged from 25 to 100 acres. The depths, in three of four cases, of the contaminated water were relatively shallow, ranging from 5 to about 60 feet below land surface. In three of the case histories, the results of the resistivity surveys, which were verified by water samples from test wells, proved to be very accurate. In the fourth case, cultural noise, depth to ground water, and relatively nonconducting leachates all contributed to a complete failure in obtaining adequate site data.

67. Topp, G.C., and J.L. Davis, "Detecting Infiltration of Water Through Soil Cracks by Time Domain Reflectometry," accepted for publication in Geoderma, 1981.

Descriptors: Dielectric Constant / Hydraulic Conductivity / Percolation / Permeability / Soil Moisture Content / Soil Tests / TDR.

TDR was used to monitor soil moisture near and at some distance from soil cracks during and subsequent to simulated rainfall. Tests were conducted in soybean and corn fields. TDR data compared favorably with estimates based on field-measured hydraulic conductivity, initial moisture content and density data.

68. Topp, G.C., J.L. Davis, and A.P. Annan, "Electromagnetic Determination of soil Water Content: Measurements in Coaxial Transmission Lines,"- Water Resources Research, V. 16, No. 3, pp. 574-82, June 1980.

Descriptors: Dielectric Constant / Laboratory Tests / Soil Moisture Content / Salts Soil Tests / Time-Domain Reflectometry.

Laboratory tests using TDR to measure moisture content of soils. Sample container was coaxial transmission line (outer conductor 5 cm ϕ, length either 0.33 or 1.0 meter) with provision for adding moisture. Electronics are described about commercial TDR system.

Soils tested include sandy loam, clayey loam, clay, organic soil, vermiculite and glass beads. Moisture included salt solutions. Data and curve fitting for polynomial regression.

Frequencies between 1 MHz and 1 GHz were used.

69. Waldrip, D.B., and R.V. Ruhe, Solid Waste Disposal by Land Burial in Southern Indiana, Indiana University and U.S. Department of the Interior, NTIS Publication No. PB-239225, 1975.

Descriptors: Landfills / Solid Wastes / Water Quality / Ground Water / Perked Water / Water Table / Waste Disposal / Hydrogeology.

Studies were made of selected landfills in southern Indiana to determine their effect on ground and surface waters. The purpose was to define field models of the geohydrologic systems, determine ground and surface water movement, analyze changes in water quality, establish landfill criteria for protection of the water, and develop landfill site guidelines. On the three sites examined, landfill leachate was introduced into the ground and/or surface water. The level of contamination was dependent on an interrelation of the original topography, the initial soil and sediment stratigraphy, the ground and surface hydrologic system, modification of the topography and stratigraphy, and nature and volume of waste. Recommendations for location design and operation of sanitary landfills were given.

70. Zonge, R., "The Complex Resistivity Method," Zonge Engineering and Research Organization, Inc., Tucson, AZ, 1981.

Descriptors: Induced Polarization (IP) / Complex Resistivity / Data Presentation / Data Reduction / Data Acquisition Equipment / Surface / Field Applications.

Induced polarization (IP) techniques are discussed and compared to the complex resistivity method as a technique to locate and/or define subsurface anomalies, primarily in mineral and petroleum prospecting. The complex resistivity method, developed and field applied by Zonge Engineering during the last decade, is discussed. The primary advantage of complex resistivity over induced polarization techniques is the solution to electromagnetic coupling problems, which tend to create technical difficulties in high-noise environments. The proprietary decoupling methods developed by Zonge Engineering in 1973 permitted the resolution of problems associated with IP and the application of electromagnetic methods to a wider range of exploration problems. The technique has not yet been field applied to detection of leachate migration from hazardous waste sites.